SEMARAK ILMU
PUBLISHING

Journal of Advanced Research in Applied
Sciences and Engineering Technology

https://semarakilmu.com.my/journals/index.php/applied_sciences_eng_tech/index
ISSN: 2462-1943

Design and Development of Savonius Turbine for STEM Education

Nurul Asyikin Abu Bakar[1], Nujjiya A. Mu'in[1], Noorfazreena M. Kamaruddin[1,*]

[1] School of Aerospace Engineering, Universiti Sains Malaysia, 14300 Nibong Tebal, Penang, Malaysia

ABSTRACT

There are very few initiatives to engage students in learning about the sustainability of wind energy through Science, Technology, Engineering, and Mathematics education, also known as STEM. This awareness is essential for future generations to instill interest and understanding in the significance of sustainable energy. Therefore, a practical, hands-on Savonius turbine demonstration kit has been designed for Science, Technology, Engineering, and Mathematics (STEM) education. Two models of drag-driven vertical axis 2-bladed and 3-bladed Savonius turbines were built to generate electricity and integrated with a model house as part of the STEM turbine kit. It was fabricated in-house and could display power using LED lights and actuating a few mechanical devices. The experimental study in this project aims to investigate and analyze the influence of the number of blades on turbine power performance in terms of power coefficient and torque coefficient with respect to tip speed ratio. The results revealed that the 3-bladed Savonius turbine has a higher power coefficient than the 2-bladed at a tip speed ratio of 0.109. However, the torque coefficient decreased as the tip speed ratio increased due to an increase in the number of blades that eventually created a reverse torque. It is also observed that the 3-bladed turbine generated the highest power output of 1.28 Watt at a speed of 38.8 m/s. The results also discovered that all the components could run more efficiently using the 3-bladed Savonius turbine. This kit demonstrates the ability to contribute to the education system in developing countries, such as Malaysia by supporting the construction of an engaging educational process with practical integration and low production costs.

Keywords:
Savonius; turbine; power;
hydrokinetic; experiment; STEM

Received: 22 August 2022 **Revised: 4 Oct. 2022** **Accepted: 21 Oct. 2022** **Published: 31 October 2022**

1. Introduction

Global warming and the emission of greenhouse gases have become major concerns worldwide and renewable energy has emerged as a significant energy source that must be developed and sustained to address this issue in the future [1]. There are various types of renewable energy technologies, such as biomass, wind power, hydro, and geothermal that are safe and effective at mitigating the effects of global warming [2]. Malaysia plans to implement 50% renewable energy by 2050 [3]. Wind energy has the ability to generate electricity with the lowest environmental impact of all the existing renewable energy sources. According to Renewables 2020 Global Status, solar photovoltaic (direct current) expansions accounted for 57% of total renewable power capacity

---

[*] *Corresponding author.*
E-mail address: fazreena@usm.my

https://doi.org/10.37934/araset.28.2.334347

increases, followed by wind power (30%) and hydropower (8%). The remaining 5% came from bio-power, geothermal power, and concentrated solar thermal power [4].

A proactive effort to empower STEM must be made to ensure that students are equipped with the essential skills to face the challenges of developing technologies to assist Malaysia in becoming a developed nation. In Malaysia, the number of students enrolled in STEM subjects has decreased, indicating that the ratio of science classes to art classes has been one to five in the last decades [5]. Kampen et. *al.,*[6] conducted a comprehensive study to emphasize the learning process related to this renewable energy on the student, which primarily employed traditional lecture-based methods and should be replaced with problem-based learning (PBL) that involves hands-on activities. The science kits in STEM education would develop the students' metacognitive abilities in their learning process to improve their critical thinking [7]. As the wind turbine kit is still uncommon in Malaysia's STEM education system, careful consideration in each step of developing the science kit is crucial to ensure that this kit enculturates the element of utilizing natural resources, to relate it to daily life activities [8] and to become most practical in STEM practices of teaching and learning process as illustrated in Figure 1.

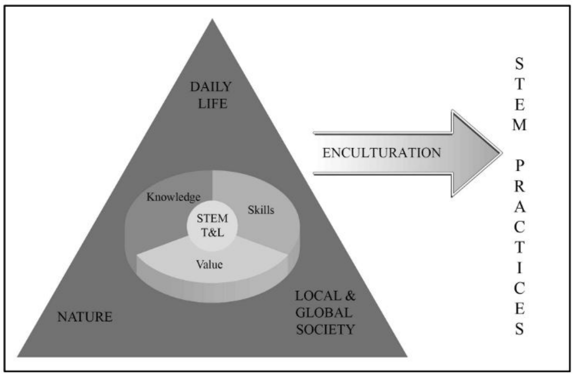

Fig. 1. The teaching and learning approach in STEM [8]

There are two types of wind turbines: horizontal axis wind turbine (HAWT) rotor shafts that operate parallel to the incoming wind flow and vertical axis wind turbine (VAWT) rotor shafts that operate perpendicular to the incoming wind flow [1]. The wind turbine is also classified based on the force exerted that rotates the turbine [9]. The HAWT has the highest efficiency in generating power compared to other turbines [10]. However, a yaw control mechanism is required to turn the wind turbine rotor toward the incoming wind flow [10]. In general, the conventional VAWT has a lower power efficiency than the HAWT [11]. Nevertheless, the VAWT is the most practical turbine to be used in this educational kit because it can operate in any direction of incoming wind flow, has a simple design and low manufacturing cost [12-16]. Furthermore, extensive research from previous studies expanded the potential of this turbine with a vast modification to the VAWT to overcome the shortcoming in its efficiency in power performance [17-21]. The VAWT includes the Darrieus turbine and Savonius turbine, which are lift-driven and drag-driven turbines based on the force that drives them to rotate. The Savonius turbine appears to be the most practical to be applied for this STEM education kit due to its simple working principle compared to the Darrieus turbine. The Savonius turbine typically operates with the incoming flow exerting a force on the advancing blades, providing a net positive torque that is represented in Figure 2 [22].

The modification of the turbine could help students to use their knowledge in real-life application as one of the potential technology applications for river-based energy extraction in Malaysia [22]. The performance of the Savonius is governed by the turbine design parameters which are aspect ratio (AR), overlap ratio (β), number of blades, turbine stages, blade shape, shaft and endplates. The presence of endplates on the top and lower parts of the Savonius blades enhances the power performance of the turbine, resulting in a higher power coefficient compared to a turbine without endplates [23]. The increase in performance is due to the capability of the endplates to maintain the pressure difference between the concave and convex surfaces of the blades over the overall height of the turbine [24].

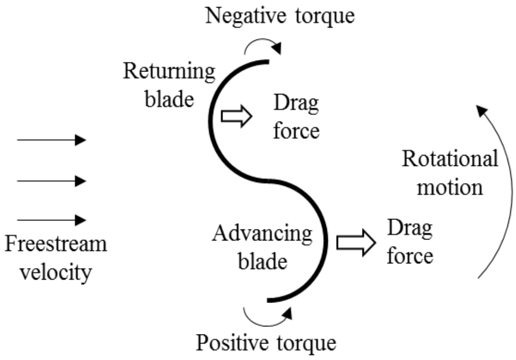

Fig. 2. The operation of the Savonius turbine [22]

The extraction of energy from the incoming wind flow is shown in Figure 3 consisting of turbine blades, support systems, main shafts, generator, bearing and electrical converter [25]. The turbine is attached to a shaft that powers up the generator. The illustration of this kit is shown in Figure 4 which illustrates the conversion of kinetic energy to electrical energy with the house components.

Before the establishment of this kit, the generator which converts mechanical energy into electrical energy was the most important component of this kit. Therefore, the selection of the generator is crucial for maximizing the energy conversion from rotational motion into electrical energy. The main types of wind turbine generators are direct current(DC), alternating current (AC) synchronous and AC asynchronous generators [26]. The most common generator used in small wind turbine applications is the DC Permanent Magnet Generator [27]. These electromechanical devices function by the interaction of the magnetic flux and electric current or flow of charge based on Faraday's law of electromagnetic induction. The DC motor operates on direct current and consists of a stator with a permanent magnet that generates a magnetic field and a rotor that carries the current. The Savonius wind turbine from the previous study used a DC permanent magnet motor as a generator with a power of 350W and a rotational speed of 2700 RPM [28]. Another study utilized a similar generator with a power output of 5.9W from a Savonius wind turbine [29]. Previous studies have established the DC generator can be used to extract electricity from small wind turbines.

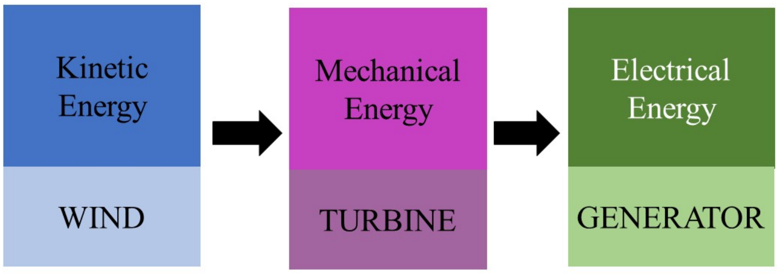

Fig. 3. The energy conversion illustration was modified from [25]

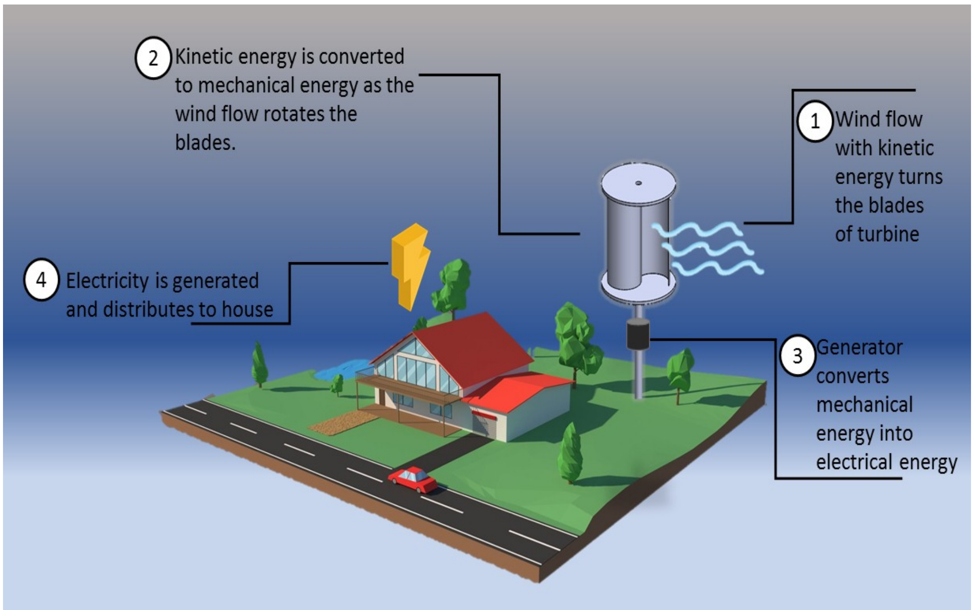

Fig. 4. The overall configuration of the Savonius turbine kit illustration modified from [25]

The present work aims to develop a learning kit based on a 2-bladed and 3-bladed Savonius wind turbine that is capable of demonstrating the power extraction process and analyzing the power performance. The development of this kit is aligned with the Malaysian Educational Blueprint 2013-2025 [8] to promote practical knowledge and understanding of renewable energy. The drag-driven Savonius turbine dimension for this STEM educational kit was selected based on the previous study [30] due to its simple working principle and ability to function at a low tip speed ratio with the DC permanent magnet generator selected for the conversion system. This generator was able to be utilized in the kit to extract the electrical power to avoid the need for a rectifier circuit, making the circuit compact, simple, and low-cost [31].

2. Methodology

In constructing the Savonius turbine kit to increase the awareness of renewable energy among the students, the design has an approach to visualize the basic working principle of energy generation from the turbine to increase their understanding [32]. The Savonius turbine will demonstrate the airflow on the turbine and convert the process into energy, while the house kit consists of electrical components that will demonstrate and display the output process. The quantitative measurement was used to analyze the power performance in terms of the coefficient of power and coefficient of torque with respect to the tip speed ratio.

2.1 Design and Fabrication of Savonius Turbine

The Savonius turbine model constructed in this project was designed using *Solidworks* software. The CAD design consists of 2-bladed and 3-bladed Savonius turbines with identical dimensions consisting of a height of 0.1 m and a diameter of 0.12 m resulting in an aspect ratio of 1. The blades of the rotor had a semicircular profile with a diameter of 5×10^{-5} m and a thickness of 0.005 m thick aluminium. The blade was attached to a fixed central shaft of 0.01 m. This turbine includes endplates to cover the top and lower parts of the blades. Fig 5 shows the CAD design of the 2-bladed and 3-

bladed Savonius turbines fully assembled with all components. The fabricated turbine is shown in Figure 6.

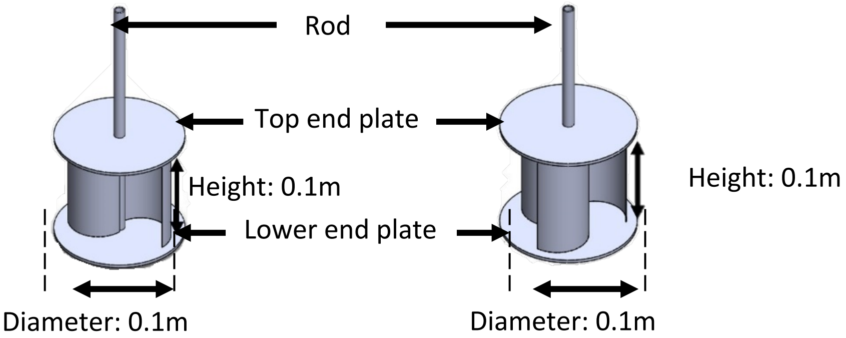

Fig. 5. The conceptual design of 2-bladed and 3-bladed Savonius turbine

Table 1
Savonius turbine components material and dimension

Components	Material	Dimension
Turbine blade	Aluminium	Height: 0.1 m Thickness: 0.0005 m
Rod shaft	Aluminium	Length: 0.25 m Diameter: 0.01 m
Top endplate	Perspex	Diameter: 0.12 m Thickness: 0.0025 m
2-bladed bottom endplate 3-bladed bottom endplate	Perspex	Diameter: 0.12 m Thickness: 0.0025 m

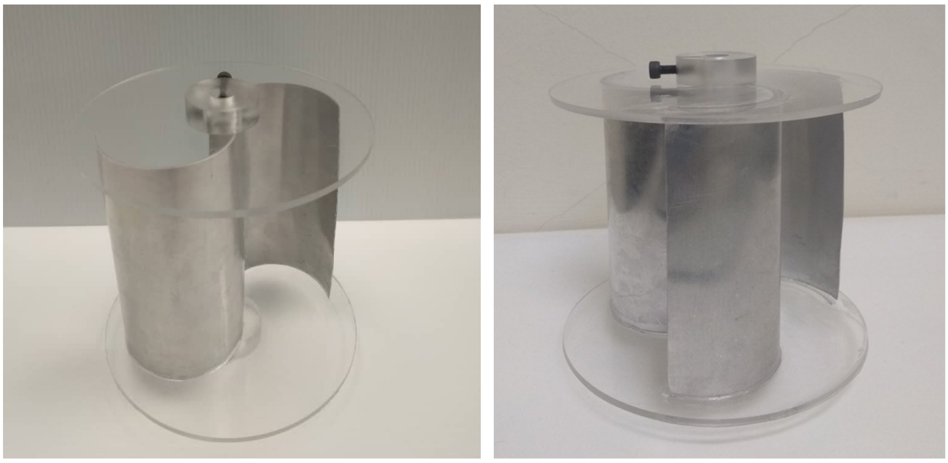

Fig. 6. The Assembly of 2-bladed and 3-bladed Savonius turbines

2.2 Fabrication of Model House Kit

This study utilized a model house kit to demonstrate the visual or qualitative analysis of this STEM educational kit. To make this kit more engaging for the students, visual and auditory representations were used to display the output of this kit, allowing the students to explore the turbine's capability to generate electricity. The model house consists of an LED lamp, a sliding gate and a monoaural speaker powered by electricity generated by the Savonius turbine as shown in Figure 7.

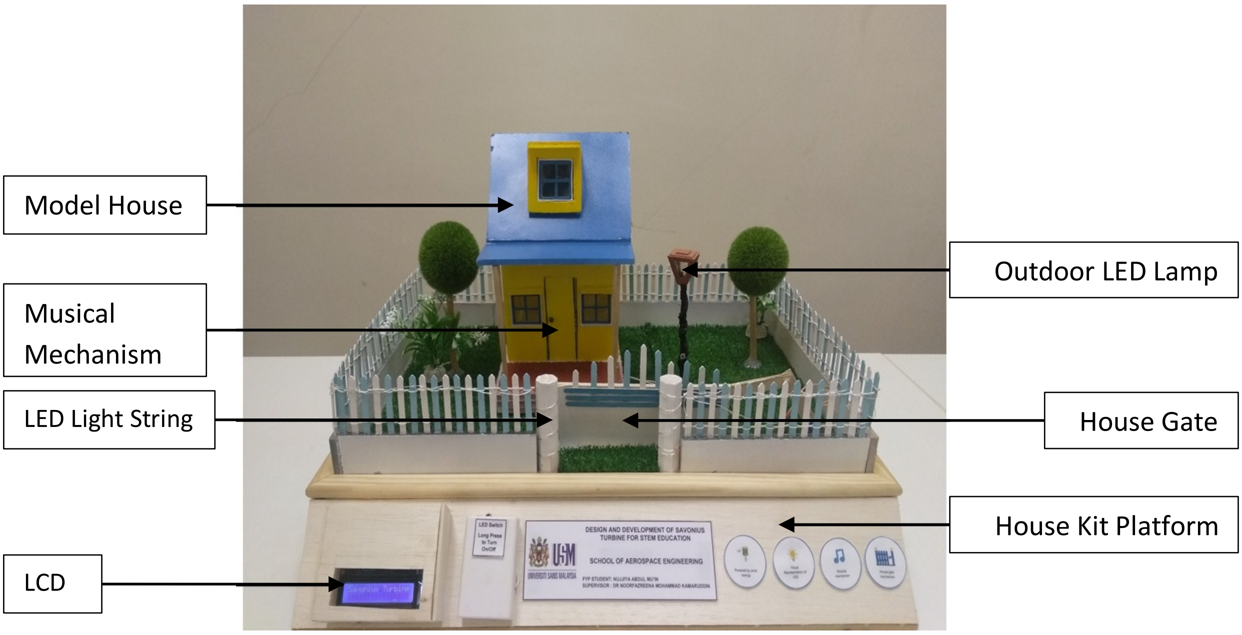

Fig. 7. The Model house (new)

The LED light was employed as one of the visual representations of the turbine's output which is part of the electrical system. There are two types of LED light used in this model house: a circular through-hole LED and a multicolor LED string as the LED enables the projecting of various range of colors. The house gate sliding mechanism is another visual representation that demonstrates the mechanism for opening the gate by moving the gate of the house. The servo motor is used to construct the sliding mechanism of the gate. Considering the importance of the auditory sense in grabbing the attention of the student, a musical module board was utilized to produce sound when the house door is opened. The Arduino Uno is used as the microcontroller with the servo motor to construct the automation system of the sliding gate moving feature in the kit.

2.3 Integration of Components Setup

The electronic components of the model house were connected to the generator in this kit. The platform is built of PVC pipe as shown in Figure 8, which serves to hold the generator and enables the Savonius turbine to rotate on the platform and consists of bearings, a timing belt pulley, a rod shaft, and a generator.

The instruments in Figure 9 were calibrated to ensure the accuracy of the reading such as a digital multi-meter, anemometer and tachometer. For example, the digital multi-meter displayed the exact voltage of the 9V battery when the test probe was in contact with the battery. The reading for the rotational speed was obtained using a digital tachometer by applying reflective tape to the turbine blade and the blower supplied the wind to rotate the turbine.

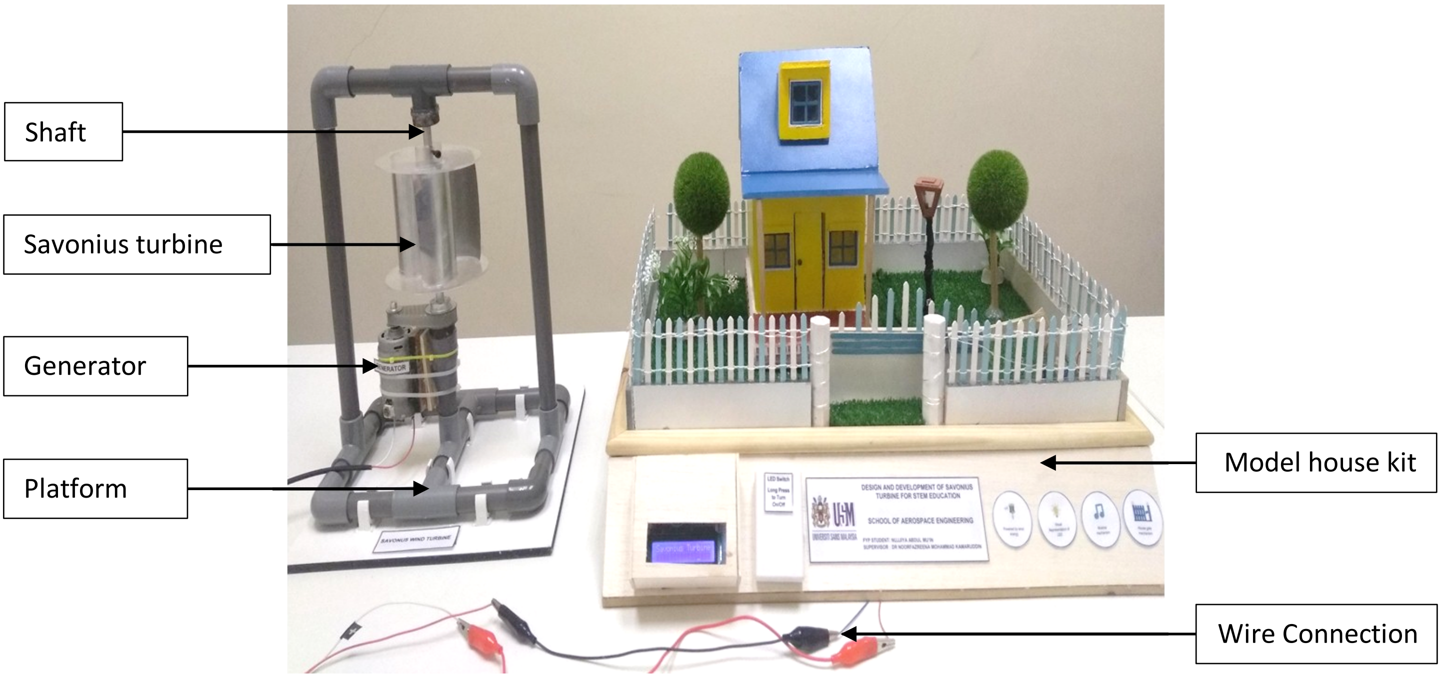

Fig. 8. The model and devices

Apparatus:

1. MT400 Maktec Blower
2. Electrical wires
3. Brannan Anemometer
4. Digital multimeter
5. DT-2234C+ digital optical Tachometer

Fig. 9. The apparatus of the experiment setup

The experiments were conducted at room temperature with wind speeds ranging from V=20 m/s to V= 38 m/s using the blower as shown in Fig 10. The rotational speed of the turbine was measured and recorded using the digital tachometer. The anemometer was used to measure the wind speed with the output voltage and current being measured using the multimeter. The output power was calculated using Equation 7.

Fig. 10. The position of the blower to the Savonius turbine

2.4 Equations

The performance of the Savonius wind turbine can be analyzed in terms of the coefficient of power C_p and torque coefficient C_t with respect to the tip speed ratio or TSR (λ). TSR is the ratio of the speed of the tip blade to the wind speed through the blade. TSR can be determined as Eq (2.1) [33]:

$$\lambda = \frac{Vrotor}{V} = \frac{\omega . d}{2V} \tag{1}$$

where $Vrotor$ is the l velocity of Savonius rotor (m/s), ω is the angular velocity of the turbine (rad/s), d is the diameter of the blade (m) and V is the wind speed (m/s). The maximum available power contained in the wind can be calculated based on the following Eq (2.2):

$$P_{max} = \frac{1}{2}\rho A V^3 \tag{2}$$

where P_{max} is maximum available power (W), ρ is the density of the air (kg/m³) and A is the swept area of the turbine (m²). For a vertical-axis wind turbine, the swept area *A= D×H* where *D* and *H* is the diameter and height of the turbine (m) accordingly. Additionally, the mechanical power extracted by the turbine is given by Eq (2.3):

$$P_{rotor} = T\,\omega \tag{3}$$

where P_{rotor} is the mechanical power extracted by the turbine (W) and T is the torque generated by the turbine (Nm). Due to the necessity of maintaining the continuity of the wind passing through the turbine rotor and some losses in the energy conversion process, the turbine can only produce a portion of the kinetic energy. This turbine performance analysis is quantified by the power coefficient, C_p, which is the ratio of the extracted power to the available power, expressed as Eq (2.4):

$$C_p = \frac{P_{rotor}}{P_{max}} \tag{4}$$

Then the torque coefficient C_t , Eq (2.5) is given as the torque produced by the turbine rotor to the maximum torque available (Patel et al, 2016).

$$C_t = \frac{T}{\frac{1}{4}\rho D^2 H V^2} \tag{5}$$

The functional relationship between C_p and C_t, which is reduced by all the above equations, is:

$$C_p = C_t\,\lambda \tag{6}$$

The output power, P (W) can be calculated by the reading of voltage output and current output based on the following equation, Eq (2.7) :

$$P = Vo \times I \tag{7}$$

where P is the output power (W), Vo is the voltage (V) and I is the current (A).

3. Results and Discussion

This section presents quantitative and qualitative data to evaluate the performance of the Savonius turbine kit and the functionality of the components of the home kit. The airflow speed ranges between 20 m/s and 38 m/s for both Savonius turbine performances. The experimental results were used to calculate the power and torque coefficient of the Savonius turbines. The qualitative result demonstrates the functionality of the components and the impact of employing various Savonius turbine configurations. Table 4.2 lists the output power in Watts. The comparison showed that the current study has a higher output power due to the capability of the 2-bladed turbine to extract wind energy more efficiently from the wind.

Table 2
Comparison data for the 2-bladed Savonius turbine

Previous studies	Output Power (W)	The output power of the current study (W)
Abubakkar [34]	0.67	0.64
Tabassum *et al*., [35]	0.62	0.65
Gatabaki[36]	0.60	0.62
Rosmin *et al*., [37]	0.30	0.32
Zien *at el*., [38]	0.24	0.21

3.1 The Performance of the 2-Bladed and 3-Bladed Savonius Turbine

The power and torque coefficient curves are plotted with respect to the tip speed ratio in Figure 11 and Figure 12 to investigate the influence of the number of blades on its power performance. Figure 11 shows the power coefficient for both 2-bladed and 3-bladed Savonius turbines. The results revealed that generally, the values of C_p tend to increase with respect to the increment of the tip speed ratio[39][40]. The 3-bladed turbine has a higher coefficient of power than the 2-bladed turbine. The maximum coefficient of power, C_{pmax} for the 3-bladed turbine, is 0.0035 at λ =0.109 while the 2-bladed turbine is 0.0021 at λ = 0.101. This is due to the 3-bladed turbine's capability to extract the flow as a result of reduced drag force on the returning blades, which consequently produced in less negative torque and allows the turbine to spin at its maximum rate.

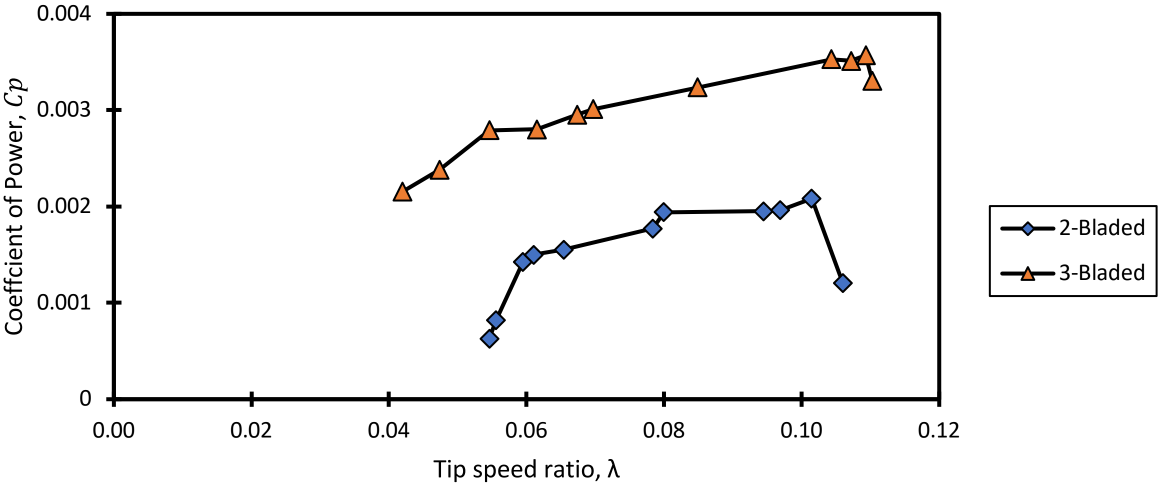

Fig. 11. The coefficient of power variation with tip speed ratio for the 2-bladed and 3-bladed Savonius turbine

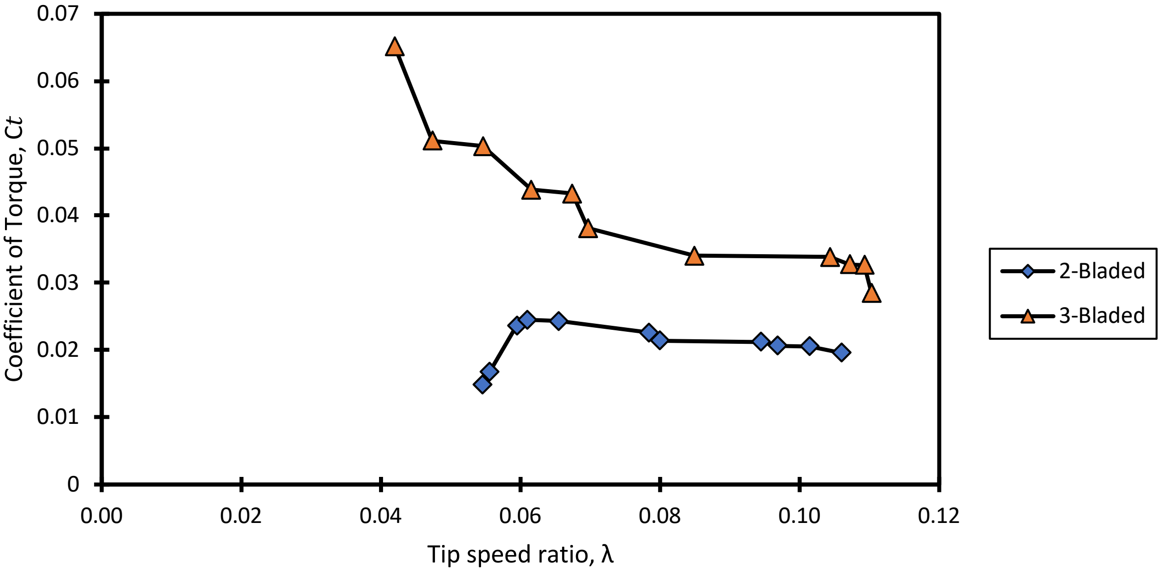

Fig. 12. The coefficient of torque variation with tip speed ratio for the 2-bladed and 3-bladed Savonius turbine

The coefficient of torque, C_t against the tip speed ratio graph in Fig 12 demonstrates that C_t decreases with the increment of λ with the C_t curve for the 3-bladed turbine was slightly higher than the 2-bladed turbine. The experimental data revealed that the C_t that corresponds to the C_{pmax} of the 3-bladed occurred at 0.0326 which was higher than the C_t that corresponds to the C_{pmax} of the 2-bladed turbine. The increasing value of C_t was due to the increased number of blades that reduce the drag which leads to a decrease in the reverse torque and consequently increase in the net torque acting on the blades of the Savonius turbine.

Based on Table 3, C_{pmax} for the 3-bladed turbine is slightly higher than C_{pmax} of the 2-bladed turbine. The power of the 3-bladed and 2-bladed turbines was 1.28W and 0.65W, respectively, corresponding to the λ of 0.109 and 0.101. As the wind flowing towards the turbine increases, the turbine will rotate at higher RPM. The Savonius turbine rotates when there is a difference between the drag force exerted by the wind on the advancing or returning blades. Hence, as the wind speed approaching the turbine blades increases, the Savonius turbine can rotate faster. The energy required to power the Savonius turbine model house is around 1.47 W. The power output of the 3-bladed turbine to generate electricity for the model house was 1.28W which was slightly closer to the required power output to generate electricity for the model house. The lower output power of the 2-bladed was caused by the loss of energy when the DC motor used as a generator caused the loss in power when its mechanical energy was converted to electrical energy in the DC generator.

Table 3
Summary list of C_{pmax} with respect to the C_t, λ and λ_{max} of the 2-bladed and 3-bladed Savonius turbine

Turbine blade	C_{pmax}	C_t at C_{pmax}	λ at C_{pmax}	λ_{max}	Rotation of turbine (RPM)	Power (W)
2-bladed	0.0021	0.0205	0.101	0.106	716.8	0.65
3-bladed	0.0035	0.0326	0.109	0.110	810	1.28

3.2 The Mechanism of the House Kit Components

The model house mechanisms such as LED light, gate and musical mechanism for the 2-bladed and 3-bladed turbines were investigated at various RPM. The outdoor house LED mechanism displays the LED light at a higher intensity in both cases. This demonstrated that the Savonius turbine could provide sufficient power for outdoor LED lights even at lower RPM, as the LED strings become brighter when the power and RPM are increased. At a higher RPM of 716.8 with a power of 0.646 W, the LED string illuminated with more luminosity than at a lower RPM of 400 with the same power. Meanwhile, the sliding gate demonstrates no movement at an RPM of 700 corresponding to a power of 0.61 W. This has caused the required operating voltage for Arduino to decrease as the gate mechanism requires a servo motor to move the gate. The 3-bladed Savonius exhibited superior performance to power at 810 RPM with a power of 1.28W. The 2-bladed turbine has a limited capability to power the music module. However, when the RPM gradually increased, the music volume increased from a low sound to a loud sound at 516 RPM with a power of 0.47W. The 3-bladed turbine presents better capability with the buzzer starting to produce a clear musical tone. This suggests that the 3-bladed turbine could produce a loud sound at a lower RPM.

4. Conclusions

A Savonius turbine STEM KIT has been developed as an interactive way to facilitate and engage the visual and auditory senses based on 2-bladed and 3-bladed design configurations. The experiments were performed at a wind speed between 20 m/s to 38 m/s to evaluate their power performance in terms of power coefficient, C_p and the torque coefficient, C_t with respect to the tip speed ratio, λ. The output power (W) produced by both turbines was also obtained. The conclusions from the present work are as follows:

1. The values of C_p were observed to increase with respect to the increment of the tip speed ratio. The 3-bladed Savonius turbine has demonstrated a higher coefficient of power than its 2-bladed counterpart. The maximum coefficient of power, C_{pmax} for the 3-bladed turbine was 0.0035 at λ =0.109 whereas the 2-bladed turbine was 0.0021 at λ = 0.101, respectively. The number of blades showed a significant influence on the power performance of the turbine.

2. The coefficient of torque, C_t decreased with the 3-bladed exhibiting the highest C_t compared to the 2-bladed. The C_{tmax} of the 3-bladed is found 0.0326 at λ = 0.042 but for the 2-bladed it was observed to be 0.0205 at λ = 0.061. The increasing value of C_t was caused by the increase in the number of blades which eventually reduced the drag and consequently reduced the reverse torque and generated an increase in the net torque acting on the blades of the Savonius turbine.
3. The performance of the 3-bladed turbine was superior to the 2-bladed turbine in terms of power output. The 3-bladed turbine exhibited a maximum power of 1.28 W at 810 RPM at a speed of 38.8 m/s, whereas the 2-bladed demonstrated the highest power of 0.65W at 716.8 RPM at a speed of 37 m/s. The lower value of output power on the 2-bladed was due to the losses of energy conversion as the DC motor used as a generator caused the loss in power when its mechanical energy was converted to the electrical energy in the DC generator.
4. The visual representation of LED for both turbines indicated that the turbine had effectively generated electricity for the LED string and exterior part of the house model. As the RPM increases, the brightness of the LED also increases with the 3-bladed turbine exhibiting better performance for powering the house gate compared to the 2-bladed turbine. The sliding gate demonstrated zero movements because the 2-bladed turbine produced insufficient operational voltage to power the gate mechanism. The musical mechanism revealed that the 3-bladed turbine generated louder sound than the 2-bladed turbine.

Acknowledgment

The authors would like to acknowledge the financial support from the Ministry of Higher Education Malaysia, under the Fundamental Research Grant Scheme: (FRGS/1/2019/TK07/USM/03/02) Account No. (203.PAERO.6071433).

References

[1] Jafri, MSA Mohd. "Design and Development of Hybrid Portable Mini Wind Turbine." (2015).

[2] Sims, Ralph EH, Hans-Holger Rogner, and Ken Gregory. "Carbon emission and mitigation cost comparisons between fossil fuel, nuclear and renewable energy resources for electricity generation." *Energy policy* 31, no. 13 (2003): 1315-1326. https://doi.org/10.1016/S0301-4215(02)00192-1

[3] K. Inus, "Malaysia Will Meet 2050 Target of 50% Renewable Energy," *New Straits Times*, pp. 4–5, 2018.

[4] REN21, *Renewables 2020 Global Status Report*. 2020.

[5] Ismail, Mohamad Hisyam, Muhamad Furkan Mat Salleh, and Nurul Akmal Md Nasir. "The issues and challenges in empowering STEM on science teachers in Malaysian secondary schools." *International Journal of Academic Research in Business and Social Sciences* 9, no. 13 (2019): 430-444. https://doi.org/10.6007/IJARBSS/v9-i13/6869

[6] van Kampen, Paul, Caroline Banahan, Michael Kelly, Eilish McLoughlin, and Eoin O'Leary. "Teaching a single physics module through Problem Based Learning in a lecture-based curriculum." *American Journal of Physics* 72, no. 6 (2004): 829-834. https://doi.org/10.1119/1.1645280

[7] Siregar, Najihah Fakhirah, and Ely Djulia. "THE EFFECT OF PROBLEM BASED LEARNING MODEL ON STUDENTS'SELF-CONCEPT AND METACOGNITIVE ABILITY ON EXCRETION SYSTEM." *Jurnal Pelita Pendidikan* 9, no. 4 (2022). https://doi.org/10.24114/jpp.v9i4.18439

[8] KPM, "Malaysia Education Blueprint 2013 - 2025," 2013. [Online]. Available: http://linkinghub.elsevier.com/retrieve/pii/S0742051X10001435.

[9] Yadav, Yogendra Kumar. "A Savonius wind turbine with electric generator: Model and test." PhD diss., Clemson University, 2016.

[10] Saad, Magedi Moh M., and Norzelawati Asmuin. "Comparison of horizontal axis wind turbines and vertical axis wind turbines." *IOSR Journal of Engineering (IOSRJEN)* 4, no. 08 (2014): 27-30. https://doi.org/10.9790/3021-04822730

[11] Wong, Kok Hoe, Wen Tong Chong, Nazatul Liana Sukiman, Sin Chew Poh, Yui-Chuin Shiah, and Chin-Tsan Wang. "Performance enhancements on vertical axis wind turbines using flow augmentation systems: A review." *Renewable and sustainable Energy reviews* 73 (2017): 904-921.

https://doi.org/10.1016/j.rser.2017.01.160

[12] Zhao, Zhenzhou, Ruixin Wang, Wenzhong Shen, Tongguang Wang, Bofeng Xu, Yuan Zheng, and Siyue Qian. "Variable pitch approach for performance improving of straight-bladed VAWT at rated tip speed ratio." *Applied Sciences* 8, no. 6 (2018): 957. https://doi.org/10.3390/app8060957

[13] Rezaeiha, Abdolrahim, Hamid Montazeri, and Bert Blocken. "Characterization of aerodynamic performance of vertical axis wind turbines: Impact of operational parameters." *Energy Conversion and Management* 169 (2018): 45-77. https://doi.org/10.1016/j.enconman.2018.05.042

[14] Alaimo, Andrea, Antonio Esposito, Antonio Messineo, Calogero Orlando, and Davide Tumino. "3D CFD analysis of a vertical axis wind turbine." *Energies* 8, no. 4 (2015): 3013-3033. https://doi.org/10.3390/en8043013

[15] Möllerström, Erik, Paul Gipe, Jos Beurskens, and Fredric Ottermo. "A historical review of vertical axis wind turbines rated 100 kW and above." *Renewable and Sustainable Energy Reviews* 105 (2019): 1-13. https://doi.org/10.1016/j.rser.2018.12.022

[16] Islam, Mazharul, David S-K. Ting, and Amir Fartaj. "Aerodynamic models for Darrieus-type straight-bladed vertical axis wind turbines." *Renewable and sustainable energy reviews* 12, no. 4 (2008): 1087-1109. https://doi.org/10.1016/j.rser.2006.10.023

[17] Zhao, Zhenzhou, Dingding Wang, Tongguang Wang, Wenzhong Shen, Huiwen Liu, and Ming Chen. "A review: Approaches for aerodynamic performance improvement of lift-type vertical axis wind turbine." *Sustainable Energy Technologies and Assessments* 49 (2022): 101789. https://doi.org/10.1016/j.seta.2021.101789

[18] Saeed, Hassan A. Hassan, Ahmed M. Nagib Elmekawy, and Sadek Z. Kassab. "Numerical study of improving Savonius turbine power coefficient by various blade shapes." *Alexandria Engineering Journal* 58, no. 2 (2019): 429-441. https://doi.org/10.1016/j.aej.2019.03.005

[19] Abate, Giada, and Dimitri N. Mavris. "Performance analysis of different positions of leading edge tubercles on a wind turbine blade." In *2018 Wind energy symposium*, p. 1494. 2018. https://doi.org/10.2514/6.2018-1494

[20] Anthony, Armand Z., and Sukanta Roy. "Performance analysis of a modified Savonius hydrokinetic turbine blade for rural application." In *IOP Conference Series: Materials Science and Engineering*, vol. 943, no. 1, p. 012034. IOP Publishing, 2020. https://doi.org/10.1088/1757-899X/943/1/012034

[21] Salleh, Mohd Badrul, Noorfazreena M. Kamaruddin, and Zulfaa Mohamed-Kassim. "Experimental investigation on the effects of deflector angles on the power performance of a Savonius turbine for hydrokinetic applications in small rivers." *Energy* 247 (2022): 123432. https://doi.org/10.1016/j.energy.2022.123432

[22] Salleh, Mohd Badrul, Noorfazreena M. Kamaruddin, and Zulfaa Mohamed-Kassim. "Savonius hydrokinetic turbines for a sustainable river-based energy extraction: A review of the technology and potential applications in Malaysia." *Sustainable Energy Technologies and Assessments* 36 (2019): 100554. https://doi.org/10.1016/j.seta.2019.100554

[23] Roy, Sukanta, and Ujjwal K. Saha. "Review of experimental investigations into the design, performance and optimization of the Savonius rotor." *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy* 227, no. 4 (2013): 528-542. https://doi.org/10.1177/0957650913480992

[24] Akwa, Joao Vicente, Horacio Antonio Vielmo, and Adriane Prisco Petry. "A review on the performance of Savonius wind turbines." *Renewable and sustainable energy reviews* 16, no. 5 (2012): 3054-3064. https://doi.org/10.1016/j.rser.2012.02.056

[25] Babu, N. Ramesh, and P. Arulmozhivarman. "Wind energy conversion systems-a technical review." *Journal of Engineering Science and Technology* 8, no. 4 (2013): 493-507.

[26] Cao, Wenping, Ying Xie, and Zheng Tan. "Wind turbine generator technologies." *Advances in Wind Power* 1, no. 1 (2012): 177-204. https://doi.org/10.5772/51780

[27] Ani, Samuel Ofordile. "Low cost small wind turbine generators for developing countries." (2013).

[28] H. Subramaniam, “DESIGN AND DEVELOPMENT OF VERTICAL AXIS WIND TURBINE,” UNIVERSITI SAINS MALAYSIA, 2019.

[29] Albani, A., and M. Z. Ibrahim. "Preliminary development of prototype of Savonius wind turbine for application in low wind speed in Kuala Terengganu, Malaysia." *International Journal of Scientific & Technology Research* 2, no. 3 (2013): 102-108.

[30] Talukdar, Parag K., Vinayak Kulkarni, and Ujjwal K. Saha. "Performance estimation of Savonius wind and Savonius hydrokinetic turbines under identical power input." *Journal of Renewable and Sustainable Energy* 10, no. 6 (2018): 064704. https://doi.org/10.1063/1.5054075

[31] P. Saikumar, D. Thamaraikannan, G. Yuvaraj, and C. Yuvaraj, “Wind Energy Based Mobile Battery Charging and Battery Applications,” *Int. J. Res. Dev. Eng.*, no. March 2014, pp. 6–11, 2014, [Online]. Available: http://w.ijrde.com/attachments/article/107/2.pdf.

[32] S. Zubaidah and U. N. Malang, “Stem : Apa , Mengapa , dan Bagaimana .,” vol. 1, no. October 2016, 2016, pp. 976–984.

[33] Vermaak, Herman Jacobus, Kanzumba Kusakana, and Sandile Philip Koko. "Status of micro-hydrokinetic river technology in rural applications: A review of literature." *Renewable and Sustainable Energy Reviews* 29 (2014): 625-633. https://doi.org/10.1016/j.rser.2013.08.066

[34] Abubakkar, A., T. Ravisankar, and M. Makeshkumar. "Design and fabrication of micro wind turbine." *International Journal of Science, Engineering and Technology Research (IJSETR)* 5 (2016): 1785-1787.

[35] Tabassum, Samia, Mashudur Rahaman, Muhammad Shahriar Bashar, Saidul Islam, Afrina Sharmin, Abdullah Yousuf Imam, Azizul Hoque, Nahid Mahbub, Sayeda Khatun, and Mahfuza Khanam. "Design and Analysis of Different Types of Rotors for Pico-Turbine." *Smart Grid and Renewable Energy* 6, no. 6 (2015): 141. https://doi.org/10.4236/sgre.2015.66013

[36] M. G. Gatabaki, “Prototype Design of Savonius Turbine,” pp. 1–68, 2006, [Online]. Available: https://www.scribd.com/document/359313080/Prototype-Design-of-a-Savonius-Wind-Turbine.

[37] Rosmin, Norzanah, Ahmad Safwan Jauhari, Aede Hatib Mustaamal, Faridah Husin, and Mohammad Yusri Hassan. "Experimental study for the single-stage and double-stage two-bladed Savonius micro-sized turbine for rain water harvesting (RWH) system." *Energy Procedia* 68 (2015): 274-281. https://doi.org/10.1016/j.egypro.2015.03.256

[38] H. Zein, H. Omar, and H. M. Omar, “Designing and Manufacturing of Miniature Savonius Wind Turbine,” *Int. Eng. Conf. Exhib. IECE*, no. November 2017, pp. 4–7, 2017.

[39] Salleh, Mohd Badrul, Noorfazreena M. Kamaruddin, Zulfaa Mohamed-Kassim, and Elmi Abu Bakar. "An experimental study on the improvement of a 2-Bladed and 3-Bladed conventional savonius rotors with a deflector for hydrokinetic application." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 67, no. 1 (2020): 93-104.

[40] Shamsuddin, Muhd Syukri Mohd, Nujjiya Abdul Mu’in, and Noorfazreena Mohammad Kamaruddin. "Experimental Investigation of the Savonius Turbine for Low-Speed Hydrokinetic Applications in Small Rivers." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 94, no. 2 (2022): 29-46. https://doi.org/10.37934/arfmts.94.2.2946