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Experimental Investigation of the Power Storage System for Savonius Turbines in Wind and Water

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ABSTRACT

The Savonius turbine is practical in generating off-grid electrical power for hydrokinetic applications due to its simple design, particularly for small rivers in rural areas. However, despite many studies on methods to improve turbine performance, the electrical aspect of the turbine system is rarely discussed. Therefore, the present study aims to evaluate the performance of a simple and affordable power storage system using a conventional 2-bladed Savonius turbine. The experiment was conducted in a wind tunnel and a water channel with flow speeds of 6 m/s and 0.33 m/s, respectively, corresponding to a Reynolds number of 62700. A power coefficient of 0.09 was discovered for the wind experiment and 0.11 for the water. The total amount of energy extracted from the water was 60% less than from the wind due to the lower available power. It was observed that the tip speed ratio decreases over the charging period due to the constant current and voltage of the Lithium-Ion batteries. This will allow for a fluctuation in the amount of required current and consequently affect the torque needed to spin the generator. The findings confirmed the functionality of the electrical storage system and contributed to the low manufacturing and maintenance cost of the hydrokinetic turbines.

1. Introduction

The global economy is gradually recovering from the economic downturn caused by the COVID-19 pandemic. Governments worldwide have committed at least $12 trillion in fiscal measures to address the COVID-19 crisis in 2020 [1]. A stimulus of this magnitude can risk exacerbating carbon emissions but it can also be utilized to solve climate problems, such as through green investments and avoiding high-carbon lock-in [2]. In addition, the disruption of supply chains resulting from the recent Russia-Ukraine conflict contributed to the global increase in fuel costs [3]. The dependency on fossil fuels particularly in the energy sector should be discouraged and the development of renewable energy plants to support conventional energy generation should become the new priority for the decision-maker.

According to Sokulski [4], the major renewable energy-producing countries from 1990 to 2020 were Brazil (75.1%), Canada (66.4%), European Union (45.1%), Turkey (40.6%), Germany (37.6%),

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Italy (36.6%), United Kingdom (33.9%), and China (28%). In comparison, Malaysia accumulated only (2%) of its total energy from renewable energy sources [5]. Despite having various renewable energy sources such as solar, wind, biomass, biogas, and hydro [5], the comparison demonstrates that Malaysia still has a long way to go since implementing the Four Fuel Diversification Strategy which aimed to establish a balance between the utilization of oil, gas, coal and hydro. The policies were continuously revised and the government set a target of 20% renewable energy in the energy mix by 2025 [6]. The new policies represent the commitment of the government toward establishing renewable energy in the country, which is a great step toward a greener energy strategy.

Malaysia is a developing country in the Association of Southeast Asian Nations with a growing demand for power particularly in remote and rural areas [7]. Among various renewable energy sources, hydrokinetic turbine (HKT) is a promising area to focus on due to the abundance of rivers in Malaysia [8] with Savonius as the most practical turbine. The Savonius hydrokinetic turbine operates on the drag principle and consists of two semi-circular blades and a pair of endplates [9]. Savonius turbines have excellent self-starting characteristics, a relatively simple design, lower fabrication costs, and are less affected by the direction of the incoming flow [9,10]. Since most communities living in remote areas have access to river streams with an average flow rate of less than 1 m/s [7], Savonius HKT systems are more practicable for generating an off-grid electrical power supply. The systems are more economical and can be easily adapted without negatively affecting the environment and livelihoods of remote communities [7,11]. Figure 1 shows the basic configuration of a conventional Savonius HKT system.

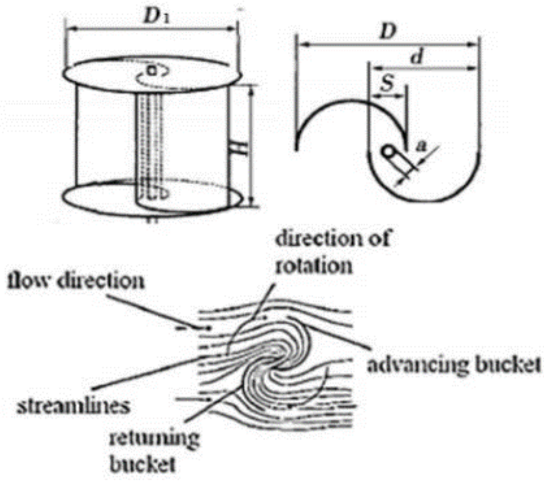


Fig. 1. Structure of a conventional Savonius turbine [12]. D is the turbine diameter, D_1 is the endplate diameter, d is the blade diameter, S is the overlap distance, and a is the shaft

Research on Savonius HKT systems has become widely available in recent years due to its promising properties, particularly for low-head and low-velocity applications [11]. For example, Ramadan *et. al.*, [13] apply a computational method to determine the power performance of conventional and S-shape Savonius rotors. They used ANSYS-Fluent software to simulate water flow speeds of 0.5, 1.0, 2.0, and 3.0 m/s. The results demonstrate that the maximum power coefficient of the S shape rotor was higher than the conventional design resulting in an overall increase of 40%. The value is based on the low water velocity conditions (0.5 m/s), which seemed to be suitable for applications along the river Nile coast in Upper Egypt as the turbine would be able to provide the necessary energy supply.

Lajnet *et al*., [14] proposed the implementation of the Helical shape Savonius rotor based on their assessment of the flow field characterizations (velocity magnitude and total pressure) as well as the performance characteristics (power and torque coefficient) of the rotors. Their rotors were created utilizing 3D printing techniques, and the study focused on other characteristics such as overlap distance and helical blade configurations. The SST *k-ω* model was used in their transient simulation method which was validated with a wind tunnel experiment at 9 m/s wind speed. The findings revealed that increasing the overlap distance of a Helical Savonius rotor reduces the velocity, degrades the total pressure distribution particularly at the level of the rotor blades, and decreases the overall net torque. In terms of the blade configurations, a novel helical Savonius rotor design characterized by delta blades was developed, with an optimum power coefficient C_{Pmax} value of 0.14 (or a total of 14.51% increased as compared to a conventional Helical turbine).

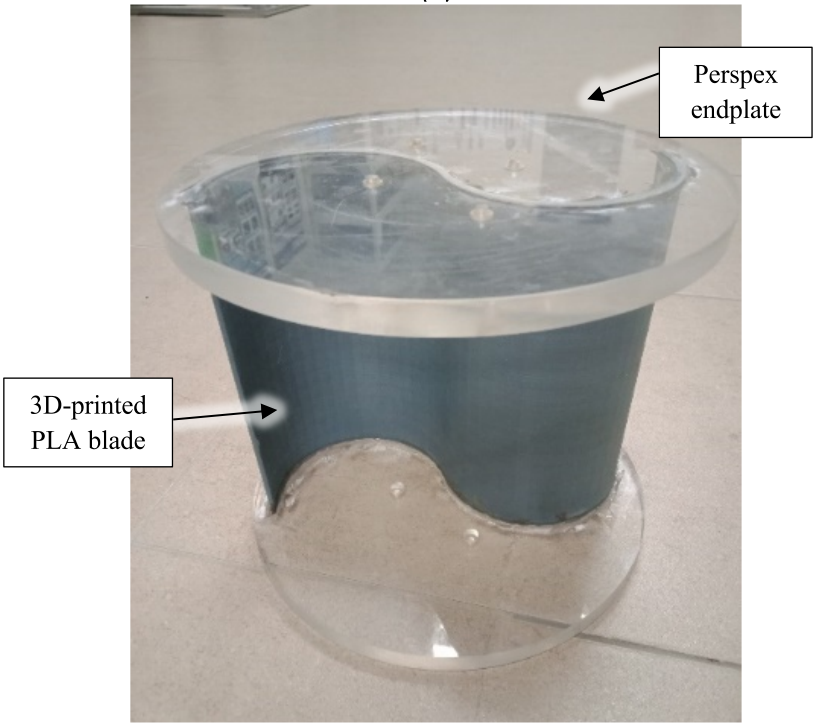
Meanwhile, Salleh *et al*., [15] investigated the effects of deflector longitudinal position and height on the power performance of a conventional Savonius rotor. Their work is intended to determine the optimal position and height of the deflector system, which serves as an augmentation device to improve the performance of the turbine. The study involved an experimental investigation in a wind tunnel facility with a wind speed of 8 m/s. A flow visualization study was also conducted to observe the flow structure across various deflector configurations. The experiment concluded that the optimal longitudinal positions of the deflectors were achieved at X_A/R = −0.500 and X_R/R = −1.204, whereas the optimal deflector height was achieved at 1H (1 time the turbine height). The highest C_{Pmax} employing optimal configurations was 0.24, representing an approximately 100% increment over those without a deflector.

Most recent work on the Savonius HKT system has usually focused on the performance and characterization of the flow around the Savonius rotors. This includes methods for optimizing the design configuration flow [9,10,13,14], as well as various augmentation devices to improve the rotor performance [15,16]. However, despite the higher performance, the mechanical energy from the optimized rotor still needs to be converted and stored as electrical energy and very limited studies have been conducted on an actual turbine electrical system. Therefore, the current work aims to establish a simple but functional electrical turbine system for storing all mechanical energy extracted from the turbine rotor. The primary design aspect is the cost of each component, which has been minimized such that the system is compatible with the practical application of the turbine (which is for the electrification of poor communities living in rural and remote areas). The proposed electrical system is functional, affordable, simple, and should work well for both wind and water applications.

2. Savonius Turbine with the Electrical Storage System

A conventional 2-bladed semi-circular Savonius rotor was used in this experimental study. The turbine was constructed from two Perspex endplates and 3D-printed Polylactic Acid (PLA) blades as shown in Figure 2 (a). The height and diameter of the turbine were H = 0.135 m and D = 0.165 m, respectively. The turbine had an aspect ratio, AR, of 0.8 with an endplate ratio, ER, of 1.1. The turbine was placed using a square Aluminium frame with a dimension of (0.6 x 0.6 x 0.6 m). A converging nozzle with a contraction ratio of 0.45 was placed at the opening of the Aluminium frame to increase the flow velocity according to Bernoulli's principle [17]. The Savonius rotor was mounted in the middle of the test section height, using a solid Aluminium shaft attached to a fixed bearing plate. The overall structure of the turbine is shown in Figure 2 (b). The Aluminium shaft that connects the Savonius rotor was then attached to a small electrical motor (12V rated) that serves as a turbine generator. All of the electrical components including the generator were mounted on a Perspex board attached to an Aluminium frame measuring (0.3 x 0.3 x 0.45 m) in size. The overall flow of the electrical storage system can be referred to in Figure 3.

(a)



(b)

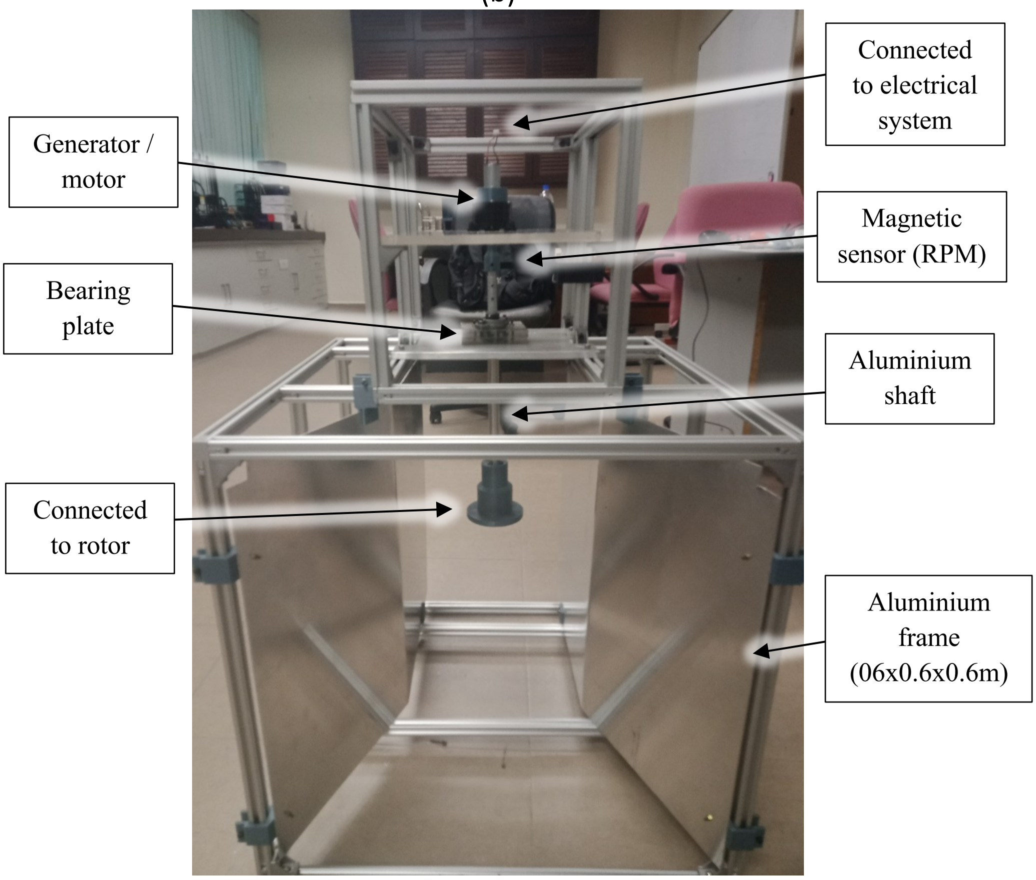


Fig. 2. Image of (a) Savonius rotor and (b) Savonius turbine system

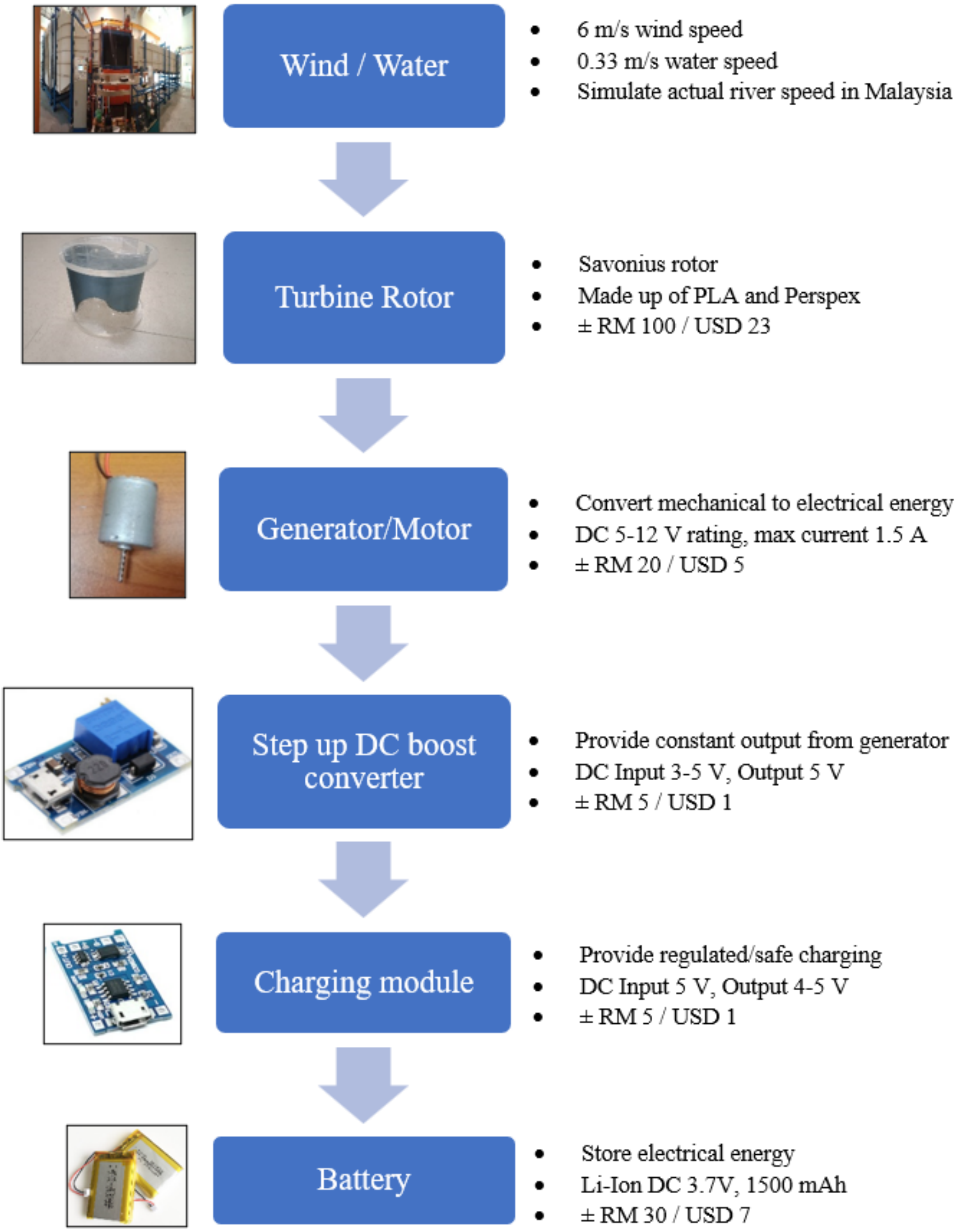


Fig. 3. Electrical storage system used in the current experiment

3. Methodology
3.1 Experimental Setup

The experiment was conducted in a closed-circuit wind tunnel facility (for wind testing) and an open-circuit water flume channel (for water testing). The wind tunnel consists of a rectangular test section of 1.8 x 0.8 x 1.0 m with a turbulent intensity of about 0.1%. The water flume channel has a test section area of 0.6 x 1.0 m and a water height of approximately 0.5 m. The wind and water speeds for both the wind and water channels were fixed at 6 m/s and 0.33 m/s, respectively, corresponding to a Reynolds number of Re= 62700.

The bottom frame of the turbine system was installed inside the wind tunnel test section for wind tunnel testing, while the upper frame and all electrical components were placed outside in the top half of the test section area. The upper frame was placed directly above the bottom frame for the water channel, where the Savonius rotor would be fully submerged in the water. The wind and water channel setup configurations are shown in Figures 4 (a) and (b), respectively.

(a) (b)

Fig. 4. Image of (a) Wind tunnel and (b) water channel setup. The blue arrow indicates flow direction

3.2 Energy and Power Coefficient

The amount of energy accumulated in this experiment is defined as the amount of energy stored in the battery storage system. The Savonius rotor was allowed to spin for approximately 30 minutes in wind and water to measure the amount of energy stored from the contribution of the turbine system. The accumulated energy can be calculated using the percentage increase in the battery's capacity, which can be calculated using the following equation

$$\%\,Capacity_{increase} = \%\,Capacity_{after} - \%\,Capacity_{before} \tag{1}$$

where $\%\,Capacity_{after}$ is the capacity of the battery after 30 minutes of charging time, and $\%\,Capacity_{before}$ is the initial capacity of the battery before charging. Note that the capacity of the battery could be measured using the actual voltage value, which could then be compared to the discharge curve from the data sheet provided by the supplier. The capacity of the battery before charging was also fixed at around 40% for both the wind and water. The percentage increase in capacity could then be translated into the amount of energy stored using the following equation:

$$E_{stored}(Wh) = \%\,Capacity_{increase} \times \ Rated\ capacity(Ah) \times Nominal\ Voltage(V) \tag{2}$$

where E_{stored} is the amount of energy stored, $Rated\ capacity$ is the capacity from the supplier of the battery (1500 mAh) and $Nominal\ Voltage$ is the rated voltage output (3.7 V). The instantaneous power out, P_{Output} from the turbine rotor can be calculated by using:

$$P_{output}\ (W) = \frac{E_{stored}\ (Wh)}{Charging\ time\ (h)} \quad (3)$$

The power coefficient of the turbine, C_P can be calculated using the ratio of power output, P_{output} divided by the power available, $P_{available}$ of the turbine, where:

$$C_P = \frac{P_{output}\ (W)}{P_{available}\ (W)} \quad (4)$$

$$C_P = \frac{P_{output}}{\frac{1}{2}\ \rho HDV^3} \quad (5)$$

where, ρ is the density of the wind or water medium (kg/m³), H is the height of the turbine (m), D is the diameter of the turbine (m), and V is the velocity of the wind or water (m/s) . The coefficients of power, C_P is dimensionless parameters that represent the efficiency of the turbine in terms of the generated power output.

Note that in a real application, the total energy accumulated by the battery system can vary depending on the battery's life cycle, which is further influenced by the depth of discharge (DoD), state of charging, and operating temperature [18]. Not to mention that some energy from the turbine rotor could be dissipated (heat, noise, etc.) during the conversion and storing process. The actual amount of energy from the turbine rotor might be higher, depending on the efficiency of each electrical component employed in the system. However, as the components were fixed throughout the experiment, the current measurement should be reliable for comparison purposes.

4. Results and Discussion

4.1 Accumulated Energy

The amount of energy accumulated in the battery storage system is shown in Figure 5. The operating conditions for wind and water channel experiments were fixed at a Reynolds number of Re= 62700, with a charging time of approximately 30 minutes. From the findings, a higher amount of energy was recorded in the case of the wind tunnel experiment. The amount of energy measured in the wind and water channel experiments was 0.135 and 0.052 W (equivalent to 486 and 186 Joules), respectively. The higher energy can be associated with the different amounts of torque applied by the wind and water forces. This result was expected because the current experiment normalized the wind and water channel flow using a similar Reynolds number condition rather than a similar power input level as conducted by Sarma *et al.*, [19]. The dynamic flow similarity would be obtained by comparing the Reynolds number with other dimensionless parameters such as power coefficient, torque coefficient, or tip-to-speed ratio. The power coefficient for the two mediums has been calculated and depicted in Figure 6. The results demonstrated that the coefficient of power is similar with only a 12% difference between the wind and water channel experiments. Note that the water channel data has been corrected using Maskell's blockage correction approach to ensure both sets of data are comparable [20]. The result agrees well with the findings of Salleh *et al.*, [21], who compare the power coefficient for wind and water channels.

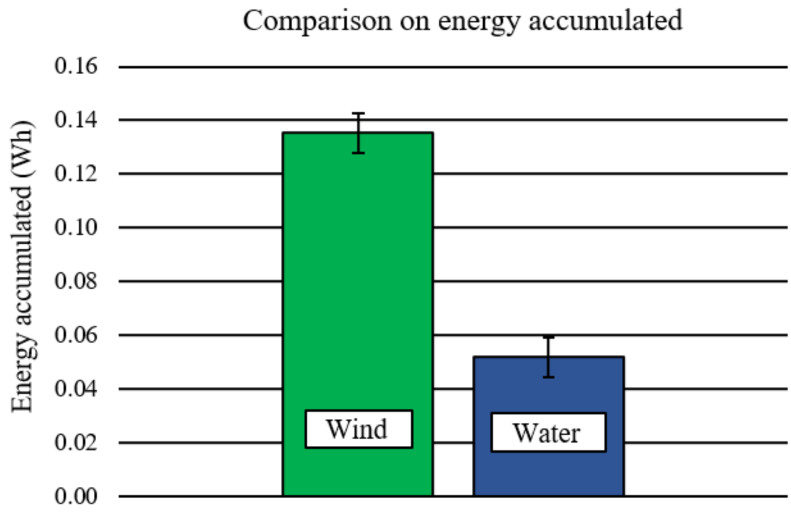


Fig. 5. The amount of accumulated energy in wind and water medium at Re = 62700

Note that although the coefficient of power, C_P is within the range of reported literature [22-24], however, the instantaneous amount of power output from the current rotor is still insufficient in comparison to the power required for common electrical appliances. The power required for common household appliances is given in Table 1. The maximum power output from the current experiment (0.27 W) is lower than the requirement for a conventional LED lamp (5 W) based on this table. These findings imply that the current turbine system is not sufficient to provide a direct energy supply to power any electrical appliances. Nonetheless, there are many ways to increase the amount of energy output from a turbine system.

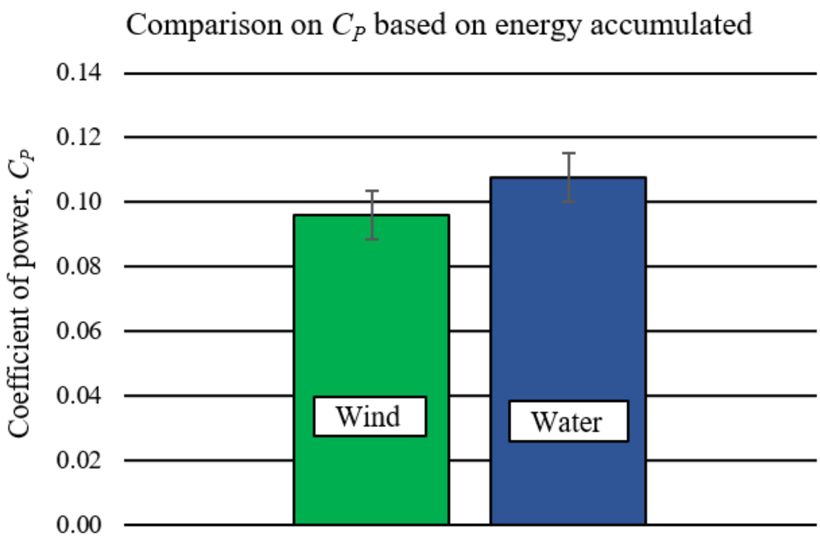


Fig. 6. The coefficient of power, C_P for wind and water medium at Re = 62700

Table 1
List of common household appliances with power requirements [25]

Common household appliances	Input power required (W)
Washing machine	1200-3000
Oven	2000-2200
Iron	1000-1800
Microwave	600-1500
Vacuum cleaner	500-1200
Electric drill	800-1000
Fridge	40-400
LCD TV	125-200
Laptop	20-50
Fan	1-36
LED lamp	5-15
Smart phone charging	2-5
Savonius rotor	**Power output (W)**
In wind tunnel	0.271
In water channel	0.104

In general, increasing the overall size of the rotor is the most apparent approach to increasing the power output of the turbine. The increased cross-sectional area through which the water or wind can flow will enhance the amount of power available. Another rotor can be stacked on top of the existing or multiple rotors can be used to increase the cross-sectional area. There are many studies to optimize the turbine coefficient of power including varying the rotor configurations [26,27], employing new or modified rotors [28,29], or using an external augmentation system [31-33].

Nevertheless, the proposed electrical system could convert and store the mechanical energy of the rotor. Although the instantaneous power output was insufficient to operate any electrical appliances, the extracted energy can still be accumulated and stored in an energy storage system. Given that the capacity of the storage system is sufficient, any electrical appliances can be powered on in a short time. This can still benefit and will be helpful to people who do not have access to the commercial electrical grid, as their electricity use will be less than that of those living in urban areas. For example, a community with easy access to the river or flowing water can simply install the turbine system and let it run for 24 hours. Although the turbine power output is small, the energy accumulated in the energy storage system would be sufficient to provide a sufficient amount to light up an LED lamp. The illumination would be temporary, but it would be good enough for them to continue their work over the night. The system is also self-sustaining, as the mechanism of the turbine will replenish the capacity of the battery over the course of the day. The cycle can continue for an extended time, or at least until the end of the battery's life cycle.

4.2 The Influence of Charging Time on Tip Speed Ratio

The tip speed ratio is defined as the ratio of the tangential speed of the tip of a blade to the actual speed of the wind or water current [21]. The tip speed ratio, TSR is given by:

$$TSR = \frac{\omega D}{2V} \tag{6}$$

where ω is the rotation speed of the turbine (radian/sec), D is the diameter of the turbine (m), and V is the velocity of the incoming fluid (m/s). The effect of charging time on the tip speed ratio is given in Figure 7.

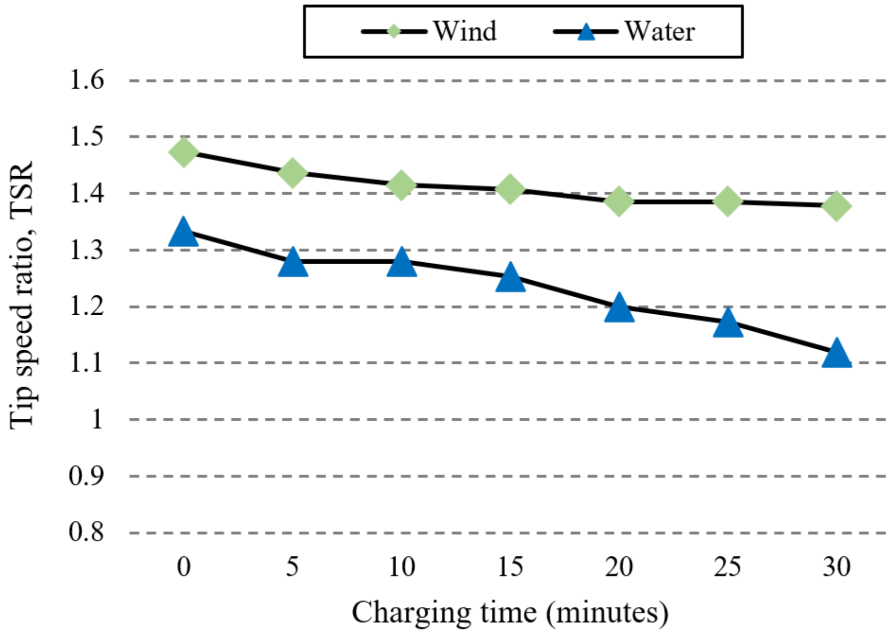


Fig. 7. The effect of charging time on the tip speed ratio

The tip-to-speed ratio, TSR based on the plot decreases with increasing charging time (up to a percentage difference of -6.1% and -15.8% for wind and water, respectively). The fluctuation of TSR is not expected because the electrical components were fixed throughout the 30 minute charging period. The only load applied to the system is the electrical storage system (a Lithium-Ion battery) which remains fixed throughout the experiment. In general, an entire battery system is made up of the battery and the battery management system (BMS). Battery charging is critical in the BMS, as charging algorithms such as charging profiles or charging currents over time significantly impact battery performance and life cycles [30]. The constant current constant voltage (CC/CV) charging method is commonly employed in charging Li-Ion batteries due to its simplicity and ease of implementation. The CC/CV charging algorithm charges the battery with a constant current until it reaches a predetermined maximum charging voltage. At this point, the charging voltage is held constant and the charging current is reduced exponentially [30]. The fluctuation current for the Li-Ion charging algorithm is most likely to have directly impacted the TSR of the turbine rotor in the present experiment. As the battery capacity is depleted, the required amount of current increases and more torque is needed to spin the generator. Consequently, the TSR of the rotor will be reduced because more energy is required to spin the turbine.

5. Conclusions

Savonius hydrokinetic turbines (HKT) provide a sustainable, cost-effective, and practical energy extraction alternative to rural communities near rivers. The present study investigates using a simple and cost-effective electrical storage system in conjunction with a conventional 2-bladed Savonius rotor. The electrical storage system was tested in the wind and water channel, with a corresponding speed of 6 m/s and 0.33 m/s, respectively, equivalent to a Reynolds number of 62700. The key findings from the present work are as follows:

1. The energy extracted from the Savonius rotor could be stored using the electrical storage system. The total cost of the electrical system including the turbine rotor was estimated to be around RM 160 (USD 37) which should be affordable for the underprivileged living in rural areas.
2. The coefficient of power, C_P for wind and water experiments were comparable at 0.09 and 0.11, respectively, using a similar Reynolds number. However, the total amount of energy extracted from the water was 60% lower than from the wind due to the lower amount of power available.
3. The tip speed ratio (turbine rotational speed) was also observed to decrease over the charging period. This is true for both wind and water channel experiments. The CC/CV charging algorithm for the Li-Ion batteries is suspected to vary the amount of current required and hence the amount of torque required to spin the generator. As a result, the resulting turbine rotational speed was reduced.

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