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Development of Integrated Renewable Energy Harvesting System

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Renewable Energy, Solar Panel, Wave Energy, Wind Energy, Wind Turbine, Harvesting System and Wave Generator.

Abstract

This research presents the development of an integrated renewable energy harvester system combining solar, wind, and wave energy into a compact hybrid prototype tailored for Malaysia's coastal environments. Addressing the limitations of standalone systems, the project aims to ensure more consistent and reliable power generation through the synergy of multiple renewable sources. The prototype, constructed using locally sourced materials such as thin-film PV panels, a Savonius rotor wind turbine, and a point absorber wave energy converter, was tested at Pantai Batu Buruk, Terengganu. Performance results show that solar power provided the highest and most stable output, while wind and wave subsystems contributed supplemental energy, especially during cloudy conditions or low sunlight. Structural tests confirmed buoyancy and corrosion resistance, validating its potential for marine use. The integration of a simple energy storage solution ensured continuous output. This study confirms the viability of low-cost, hybrid renewable systems to enhance energy resilience in Malaysian coastal areas. Further enhancements are recommended, including advanced power management systems, improved turbine and buoy designs, and larger-scale testing to support commercialization potential.

1. Introduction

Malaysia's geographic advantages — a tropical climate, high solar irradiance, and extensive coastlines — make it a promising candidate for renewable energy development, particularly in solar, wind, and wave energy [1][2]. However, current infrastructure is primarily built around standalone systems, which struggle with the intermittent nature of renewable sources [3]. For instance, solar energy is limited by weather conditions, wind is inconsistent in most regions, and wave energy is underutilized despite significant potential during monsoon seasons [4][5]. This creates a challenge in ensuring a stable and reliable energy supply. To overcome this, an integrated hybrid renewable energy harvester system is proposed, combining solar, wind, and wave technologies into one unified platform. Designed specifically for Malaysia's coastal environments, this system leverages complementary energy profiles and storage systems to ensure continuous energy production and support Malaysia's long-term sustainable energy goals [6][7].

Due to its continued heavy reliance on fossil fuels as its primary energy source, Malaysia is becoming more vulnerable economically because of shifting fuel prices, growing carbon emissions, and environmental damage [6]. Despite the abundance of renewable resources like solar, wind, and wave energy, standalone systems which are unstable owing to natural variability remain the focus of current implementations in the nation. For instance, wave energy conversion depends on enough sea motion, wind turbines need steady wind speeds to function at their best, and solar panels lose their effectiveness in cloudy or nighttime conditions [3][4]. The existing technologies are inadequate for long-term energy security because of these individual constraints, which lead to inconsistent power production. Despite Malaysia's considerable coastline wave potential, particularly during monsoon seasons, existing hybrid systems frequently only mix solar and wind energy, ignoring wave energy [8][10]. Furthermore, a lot of these systems are expensive and less sustainable in the local environment since they are constructed with foreign technology [6]. This makes a glaring hole in Malaysia's framework for renewable energy. A locally developed and built integrated energy harvester that integrates solar, wind, and wave energy into a single hybrid system is therefore desperately needed. In addition to encouraging energy independence and supporting national carbon reduction targets, the suggested system should solve concerns of dependability, affordability, and environmental adaptability [9][10].

2. Methodology

2.1 System Design

The system is a small, integrated hybrid platform that integrates wave, wind, and solar energy, making it ideal for Malaysia's coastal environment. Every energy subsystem was chosen with care to make sure it works well with the others and helps to generate electricity steadily even in the face of changing climatic circumstances. Thin-film photovoltaic panels were selected for solar energy because of their affordability, adaptability, durability in corrosive, humid maritime conditions, and lightweight design. The vertical-axis wind turbine (VAWT) used in the wind energy subsystem is the Savonius type, which is preferred for its ease of maintenance, safety, simplicity, and capacity to function at low wind speeds. A point absorber system, which consists of a floating buoy coupled to a generator, was included to collect wave energy. This system was chosen because of its ease of production, small size, and good compatibility with moderate wave conditions. To avoid mechanical interference, the design makes sure that all three energy collecting mechanisms are integrated on a single platform and supported by a balanced arrangement. The structure was developed and improved, space was optimized, and the relationship between subsystems was visualized using CAD software. To buffer energy and ensure supply continuity even if one of the sources is not in use, a simple power bank-based energy storage and management system was also incorporated.

2.2 Material Selection

Durability, cost, usefulness, and compatibility for coastal circumstances are the main considerations when choosing materials for the integrated energy harvester. Thin film technology, which keeps the solar panels lightweight and small while resisting corrosion, high temperatures, and humidity, is used in their construction. High-density polyethylene (HDPE), a material renowned for its exceptional buoyancy, impact resistance, and environmental longevity, is used to make the floating buoy for wave energy collecting. HDPE is perfect for maritime applications as it is non-toxic and consistent with environmental principles. Stainless steel fasteners are utilized in combination with the buoy to give extra structural strength and corrosion resistance. The blades of the wind turbine are made of readily available, lightweight plastic and are fixed to a DC motor that acts as the generator. This economical and efficient approach is useful for prototype testing and student projects. Square hollow stainless-steel tubing serves as the system's main support frame, providing a robust, corrosion-resistant framework that can sustain the combined mechanical stresses from all three energy subsystems. Each component was chosen to guarantee both long-term dependability and functional performance in challenging outside environments, assisting the system in achieving its dual objectives of efficiency and environmental friendliness.

2.3 CAD Drawing and Project Development

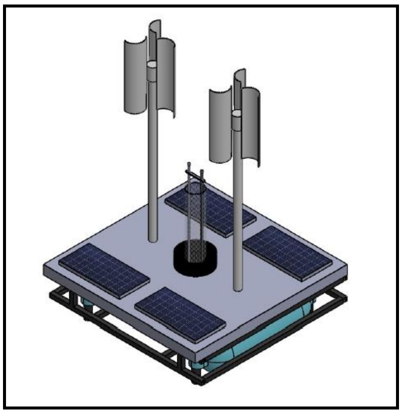

Fig. 1 The Design CAD drawing of prototype

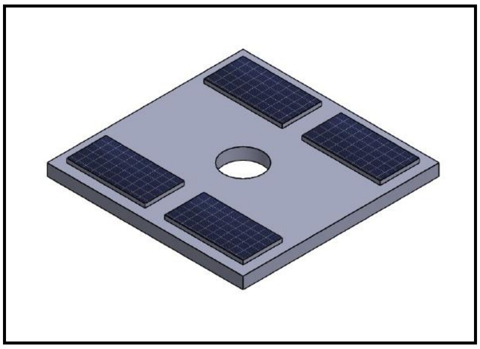

Fig. 2 The CAD drawing of Solar Panel Arrangements.

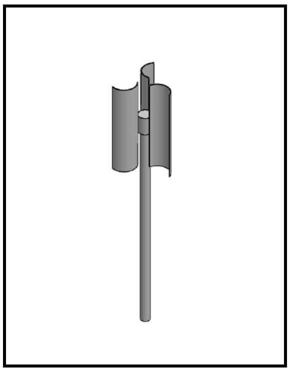

Fig. 3 The CAD drawing of Vertical Axis Wind Turbine (VAWT).

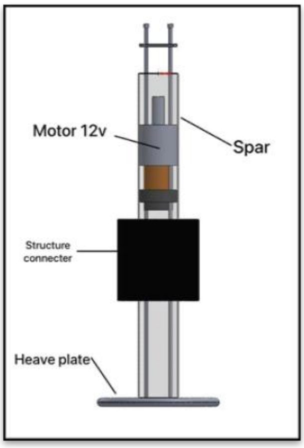

Fig. 4 The CAD drawing of Point Absorber Wave Mechanism.

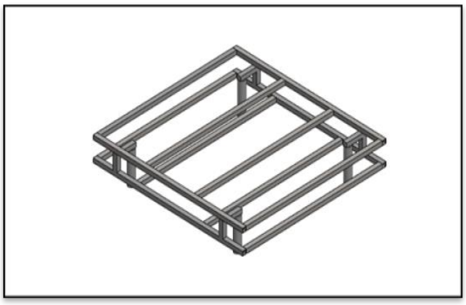

Fig. 5 The CAD drawing of The Main Structure of The System.

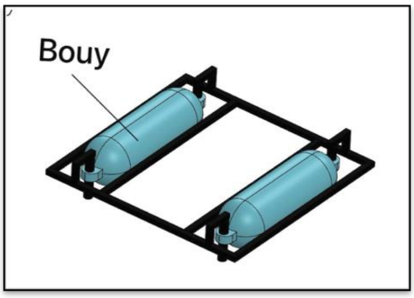

Fig. 6 The CAD drawing of The Floating Platform.

The development of the integrated renewable energy harvester system involved careful computer-aided design (CAD) and iterative prototype refinement to ensure all components could be integrated efficiently and safely on a single structure. CAD drawings (Figure 1-6) were created using SolidWorks to visualize the layout and dimensions of each subsystem, including the solar panels, Savonius wind turbine, point absorber wave mechanism, and the overall structural framework. These drawings helped determine the best positioning and spacing of each component to avoid interference and maintain balance during operation. Several iterations were made to improve the arrangement and accommodate the compact size requirements of the prototype. The solar panel array was designed to fit on the platform surface, the wind turbine was mounted vertically to catch ambient wind, and the wave mechanism was integrated beneath the platform using buoyant materials. The structure was modeled to maintain buoyancy and stability in water while supporting the mechanical loads of all components. After finalizing the design in CAD, the prototype was fabricated using materials selected for durability and environmental resistance, including stainless steel, HDPE, and lightweight plastics. The completed prototype was then assembled and prepared for real-world evaluation. This design and development process ensured that the prototype was not only functional but also practical for coastal energy harvesting applications.

3. Results and Discussion

This chapter presents and discusses the performance data collected from the integrated renewable energy harvester system, which consists of three subsystems: solar, wind, and wave energy modules (Figure 7). Testing was conducted using real-world environmental data and simplified field measurements in Pantai Batu Buruk, Terengganu. Each sub-system's energy output is analyzed individually, followed by a comparison of their theoretical and practical performance.

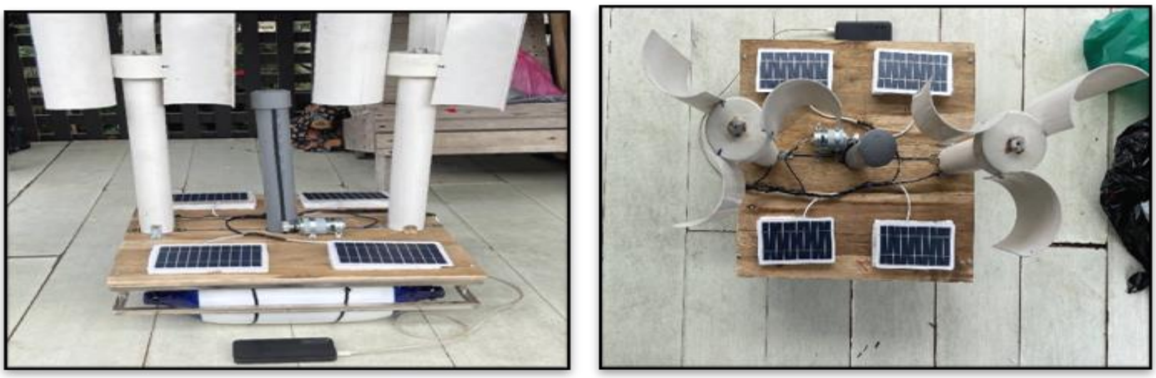

Fig. 7 The Energy Harvesting Prototype

3.1 Structural Integrity Testing

Because the prototype will operate in a challenging marine environment, its mechanical strength and material durability needed to be verified. Two tests were performed: Load Testing and Saltwater Corrosion Testing.

3.1.1 Floating Test

Floating tests were conducted to evaluate the prototype's buoyancy, stability, and waterproofing under various loading and environmental conditions (Table 1). The evaluation was carried out in two stages: initial testing in a calm river to observe basic flotation characteristics, followed by testing in a coastal sea environment to simulate real-world marine conditions. Two scenarios were tested first with only the structural frame, and then with all components installed, including the solar panel, wind turbine, wave energy converter, and battery system. In the river, the empty structure floated upright without tilting or water ingress. With the full system mounted, minor tilting of about 5° was observed due to uneven weight, but this remained within acceptable limits. In coastal sea conditions, the prototype responded to wave and wind motion with increased tilting of up to 13°, yet it remained stable and did not leak or suffer structural damage. The two-stage approach allowed for both controlled and realistic testing, confirming that the system maintains adequate buoyancy and stability for deployment in calm and moderate marine environments.

Table 1 Effect of Component Integration and Environment on Stability and Water Ingress

Condition	Stability	Water Ingress
Without Component (River)	0°	None
With Component (River)	5°	None
With Component (Coastal Sea)	13°	Minor Water Ingress

3.1.2 Exposure Test

A seawater exposure observation (Table 2) was conducted to assess the durability of the square hollow stainless steel used in the prototype's structural frame under real marine conditions. Instead of using controlled laboratory methods, the material was submerged directly in coastal seawater to observe the effects of natural environmental factors such as tidal movement, salinity, and biological fouling. The samples were left in place for seven days, after which they were visually inspected for signs of corrosion, rust, pitting, and marine growth. The results showed no significant corrosion or damage. This observation suggests that the material offers good resistance to seawater exposure, making it suitable for short-term deployment in coastal energy harvesting systems.

Table 2 Material Corrosion Assessment Following Coastal Seawater Exposure

Test Parameter	Details
Material	Square Hollow Stainless Steel
Exposure Method	Direct Coastal Seawater Immersion
Exposure Duration	7 days
Observation	No rust, no pitting, minor biological fouling
Conclusion	Excellent corrosion resistance

3.2 Solar Energy Harvester

Four The solar subsystem uses four 5V 5W portable solar panels connected in parallel to increase current and keep voltage stable. Each panel has a USB stabilizer to ensure safe and consistent output. Testing was done from 12:00 PM to 5:40 PM under strong sunlight, with solar irradiance between 850 to 1000 W/m^2 and the results were recorded as shown in Figure 8. The system was expected to produce around 20W (10V, 2A). During the test, actual output stayed close to this value, with voltage between 9.95V and 9.40V and current between 2.00A and 2.13A. Even when voltage dropped slightly later in the day, the current increased, helping to keep the power output stable.

Observations were also made on both sunny and cloudy days. On clear days, power increased in the morning and peaked at around 20W near noon. Voltage rose from 7.00V at 8:00 AM to about 10.00V by midday, with current rising from 1.20A to 2.00A. On cloudy days, the power was lower, between 2.1W and 10.5W, with voltage between 3.5V and 7.25V, and current mostly under 1.45A. Even so, the system still followed a normal pattern, adjusting output based on sunlight levels.

Overall, the results showed that the solar subsystem works well in different weather conditions and is suitable for coastal environments. The parallel setup helped maintain steady power and supported charging the power bank reliably.

3.3 Wind Turbine Harvester

Two The wind energy subsystem uses two small Savonius-type vertical-axis wind turbines, designed with three curved blades for better performance in low wind speeds. Each rotor is 60 mm in diameter and 200 mm tall, with a total swept area of 0.0200 m^2. During field tests at Pantai Batu Buruk, average wind speed was around 3.184 m/s, which is normal for Malaysia's coastal areas. The results obtained is shown in Figure 9.

On clear days, wind speed slowly increased from 1.80 m/s in the morning to over 4 m/s in the late afternoon, peaking at 4.03 m/s. As wind speed increased, so did the power output from 0.090 W in the morning to a maximum of 0.805 W in the afternoon. Voltage readings ranged from 1.0 V to 3.5 V, and current between 0.09 A to 0.23 A, showing that the system responded well to small changes in wind speed.

On cloudy days, the wind subsystem continued to operate well and even performed better at times due to stronger and gustier winds. The highest wind speed recorded on a cloudy day was 4.15 m/s at 3:40 PM, which produced 0.464 W. After 1:00 PM, the power stayed above 0.3 W, showing that the system worked well when solar power was low.

Although the wind turbine generated less power than the solar panels, it played a key supporting role especially during cloudy weather, early mornings, and evenings when sunlight was weak or unavailable. The actual output ranged between 0.2 W to 0.7 W, with estimated efficiency around 30%, which is reasonable for small wind turbines.

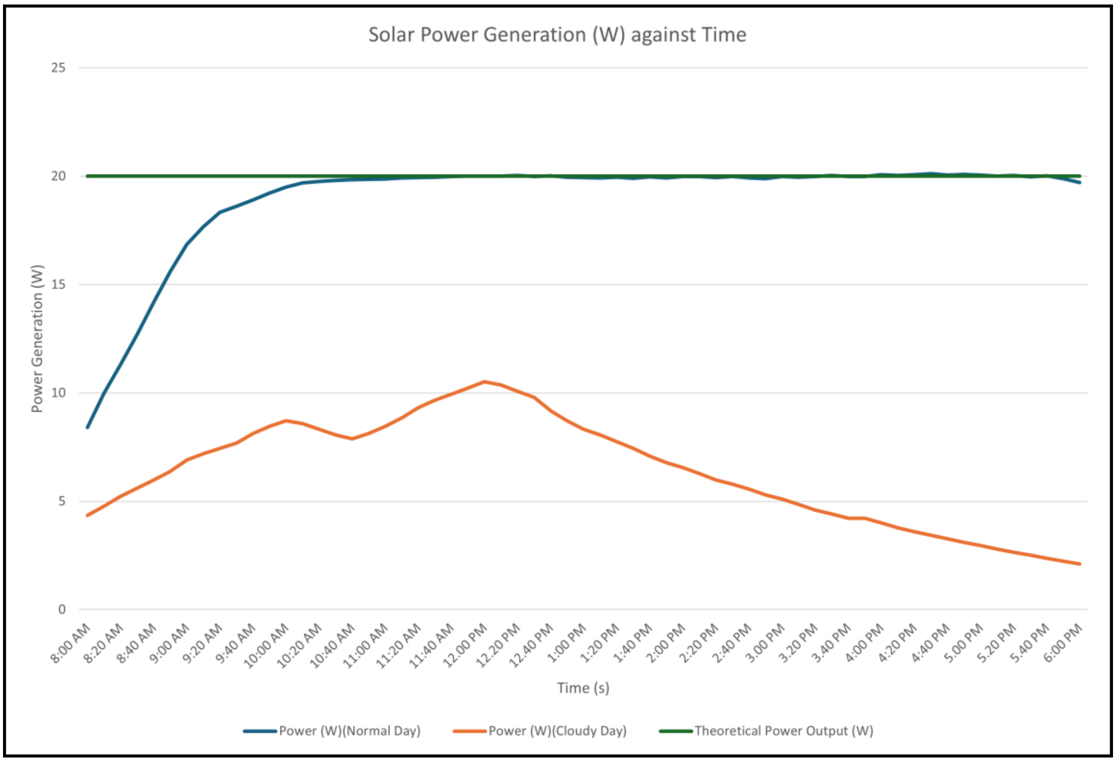

Fig. 8 Solar Power Generation vs Time

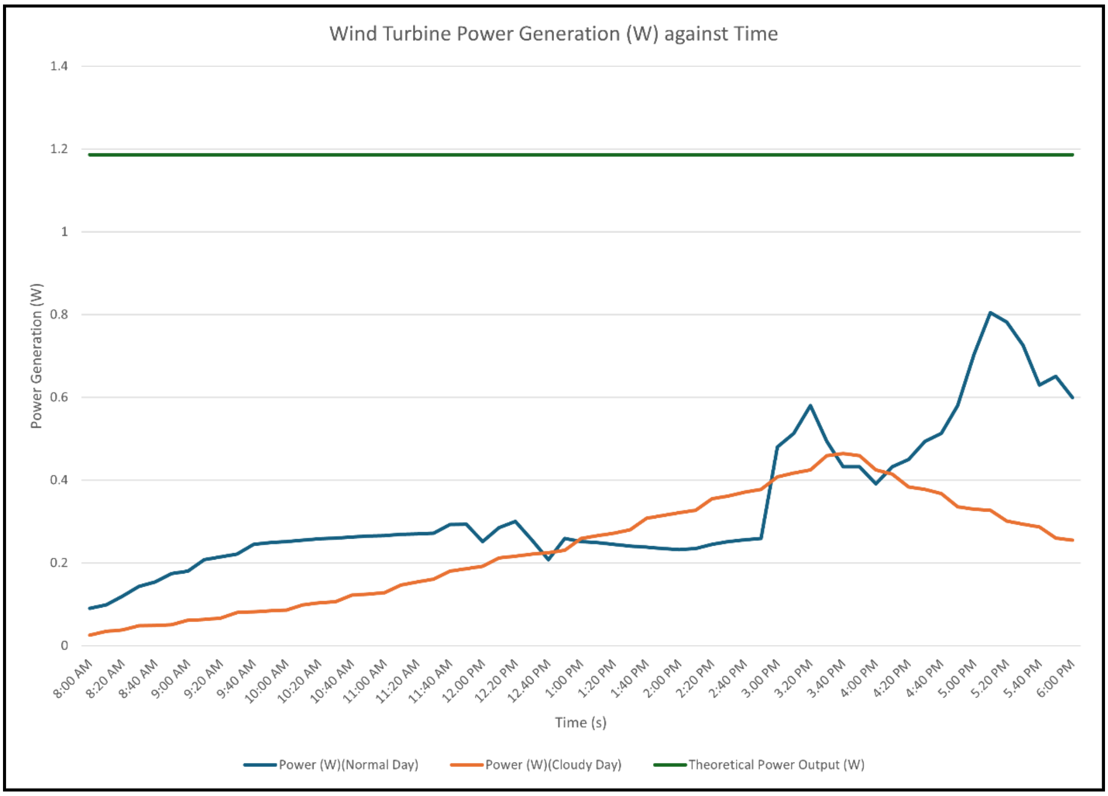

Fig. 9 Wind Turbine Power Generation vs Time

In summary, the wind subsystem contributed stable, low-level power to support the hybrid energy system. Its reliable operation under various weather conditions makes it useful for coastal or off-grid applications where continuous power is needed.

3.4 Wave Generator Harvester

The wave energy subsystem uses a point absorber buoy connected to a 12V 775 DC motor to convert vertical wave motion into electrical energy. This system was tested at Pantai Batu Buruk, where wave conditions changed throughout the day from calm in the morning to moderate in the afternoon, then back to calm in the evening. The results of power generated by wave generator is presented in Figure 10.

On clear days, the highest power output recorded was 0.217 W at 2:10 PM, with voltage at 1.55 V and current at 0.14 A, during moderate wave activity. When the sea was calm, the output dropped sharply, sometimes as low as 0.025 W, showing the system's strong dependence on active wave motion.

Similar patterns were seen on cloudy days. Although there was no sunlight, slightly rougher waves in the early afternoon helped boost energy output. The highest power recorded on a cloudy day was 0.233 W at 12:30 PM, and the system stayed above 0.15 W for most of the midday period. However, when wave motion decreased later in the day, performance also dropped.

The test results matched the theory: more wave movement leads to more buoy motion and generator rotation, which increases output. Still, because waves are not constant, the system cannot work as a standalone energy source. Instead, it works best as a supporting system in a hybrid setup with solar and wind.

In summary, the wave energy subsystem is effective when waves are present but unreliable during calm sea conditions. Its strength lies in adding extra power during times when solar or wind energy is low making it suitable for coastal or island areas where hybrid renewable systems are needed. With future improvements in mechanical design or energy storage, its contribution could be even more useful.

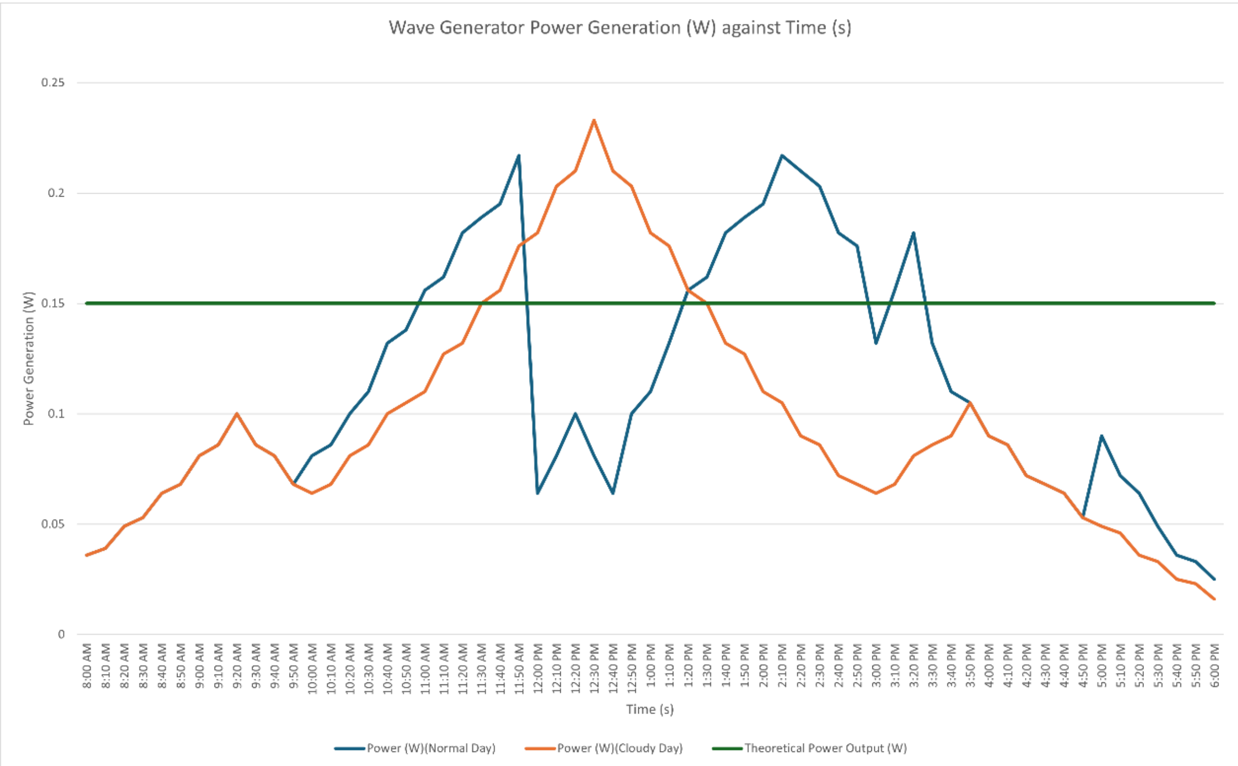

Fig. 10 Wave Generator Power Generation vs Time

3.5 Combine System Harvester

All The integrated renewable energy system, which combines solar, wind, and wave sources, showed stable and increasing power output from morning to evening on both sunny and cloudy days (Figure 11). On a clear day, the power started at about 23 W at 8:00 AM and reached a peak of 34.79 W by 6:00 PM. On an overcast day, the output was slightly lower, starting at 18.9 W and peaking at 33.44 W around 3:20 PM, showing strong support from wind and wave subsystems when sunlight was limited.

During peak sunlight hours around midday, the system produced an average of 28.33 W, mainly from the solar panels. However, the most important result was that the system maintained a power output above 30 W between 3:00 PM and 5:30 PM, even as sunlight dropped. This proves that the wind and wave subsystems helped support the system when solar energy was not strong.

Throughout the tests, the voltage stayed consistently above 12 V, which was enough to charge a Ugreen 10,000 mAh power bank. The current stayed steady between 2.2 A and 2.45 A, showing reliable energy flow. However, since USB charging typically needs 5 V, a voltage regulator like a buck converter would be needed for safe charging.

Although the exact energy share from each subsystem was not measured, the test clearly showed that solar was the main source during midday, while wind and wave energy became more important in the afternoon and on cloudy days. This balance helped reduce power drops and made the system more reliable.

Overall, the system proved capable of powering low-energy devices, charging electronics, or running small sensors in coastal or remote areas. The test at Pantai Batu Buruk confirmed that this hybrid system works well in real conditions, especially in places like Malaysia where sunlight is strong but wind and wave energy can provide backup when needed.

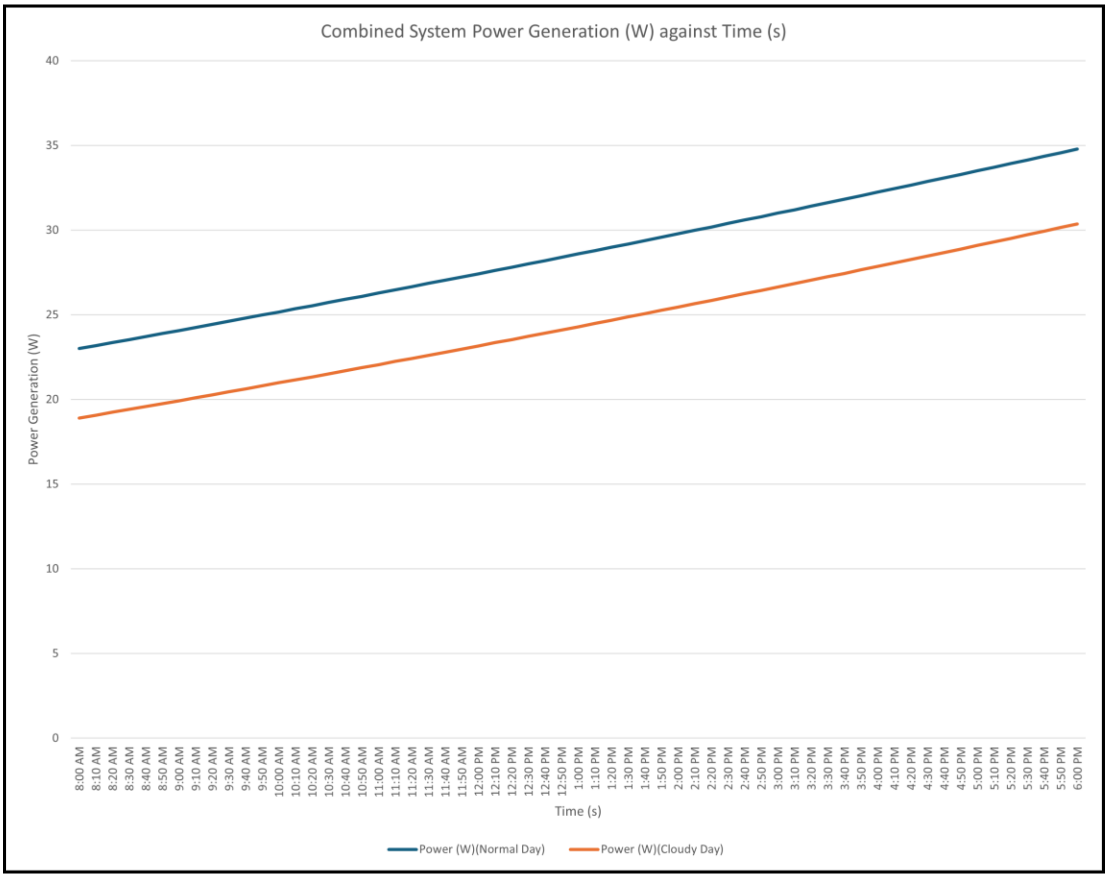

Fig. 11 Combined System Power Generation vs Time

3.6 Comparison between Individual and Combined System

The hybrid energy system, combining solar, wind, and wave sources, showed steady and reliable power output under both sunny and cloudy conditions. Solar was the main contributor, averaging over 20 W, while wind and waves provided smaller outputs but helped support the system especially in the afternoon and during cloudy periods. The total power output peaked at 33.44 W at 3:20 PM on a clear day and still reached over 30 W on an overcast day. This shows the benefit of using multiple energy sources to maintain stable performance. The hybrid setup is suitable for coastal or off-grid areas, offering a more consistent power supply even when sunlight is limited.

4. Conclusion

A small hybrid renewable energy system combining solar, wind, and wave sources was successfully built and tested. The prototype worked well in Malaysia's coastal conditions, with solar providing the highest and most stable power, while wind and wave supported energy generation during cloudy weather and evenings. The Savonius wind turbine performed well in low and changing wind, and the wave buoy added extra power when sea conditions were active. The system remained stable, floated properly, and had no corrosion issues thanks to the use of Grade 316 stainless steel. The Ugreen 10,000 mAh power bank was enough to store the energy generated. Overall, the project showed that this type of hybrid system is practical, affordable, and suitable for coastal use in Malaysia.

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