Simulation and Prototype Design of Hybrid Renewable Energy Harvesting System

Yanuar Z. Arief, Muhammad Syukri Nurulhak, and Hamzah Eteruddin

Abstract In this era of globalization, the energy harvesting technology for renewable energy has improved to combat the concerns about energy conservation, global warming, and excessive waste materials. Additionally, the problem of getting continuous and reliable energy and power supply will become a real issue in the future. The energy harvesting technology can be an alternative to the current power generation and can lead to the potential of getting a more reliable power supply for everyone. By combining multiple renewable energy harvesting systems, more power can be continuously generated, and the efficiency of energy output will increase. This paper focuses on the development of a hybrid renewable energy harvester system consisting of photovoltaic, piezoelectric, and wind energy. The system's performance and capabilities are recorded and analyzed under different conditions and parameters.

Keywords Energy harvester · Hybrid renewable energy · Photovoltaic · Piezoelectric · Wind energy · Power supply

1 Introduction

Energy harvesting refers to the harnessing of readily available energy from the surrounding into electrical energy [1]. Some of the energy harvesting technology covers the conversion of light, kinetic, thermal, and radio frequency via various mechanisms such as photovoltaic, piezoelectric, and thermoelectric [2]. The electrical energy gathered can be used directly or stored for later use. The energy harvesting

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technology can be an alternative for places with no power grid or places that are not suitable for solar panels and wind turbine installation. Energy harvesting also has become one of the most-rapid growing technologies in the current year. It is estimated that the market size of energy harvesting can reach up to USD 817.2 Million by 2026 [3]. The motivation for adopting the energy harvesting technology for renewable energy comes from the concern about energy conservation, global warming, and excessive waste materials.

However, the energy harvested is in small amounts and adequate for low-power applications such as remote sensing, body implants, and most wireless applications [4]. For start, some of the IoT devices can integrate the energy harvester system for their sustainability since it can be operated at low power. The Internet of Things or IoT can be described as billions of physical devices that are linked to the Internet to connect and exchange data [5, 6]. IoT devices can be everything if it connected to the Internet and can be interacted with or controlled. It can be as small as switching on the lamps using a smartphone application or exchanging massive data back and forth using thousands of sensors for the monitoring system.

The self-sustainable operation of IoT devices is one of the main importance that has been discussed by many researchers. For long-term accessibility, the usage of a disposable battery can be ignored, and it can be charged by itself. The energy harvesters are divided into four groups that are based on their power output, which is high power (more than 2–10 W), medium power (between 1 and 10 W), low power (between 1 mW and 1 W), and ultra-low power (below 1 mW) [7–11]. From the low-power devices, the energy harvesting system can move on to powering up the medium to high-power devices. This can lead to the integration of energy harvesting technology into various industries such as transportation, automotive, power generation, and more. There are already some existing energy harvesting devices and applications such as photovoltaic solar energy at rooftops that convert light into electric energy or use wind energy to convert mechanical energy to electrical energy [11].

This paper presents the study of four types of energy harvesters which are photovoltaic, piezoelectric, thermoelectric, and radio frequency. The energy harvester will be combined and merged to create a hybrid energy harvester. The energy harvester will be tested using simulation, and some of them will be implemented into hardware design depending on the availability and convenience.

2 Research Method

2.1 Simulation of Hybrid Renewable Energy Harvesting System

Figure 1 shows the process flowchart for MATLAB simulation for this project. It is divided into two parts, which are for photovoltaic energy harvester and wind energy harvester simulation.

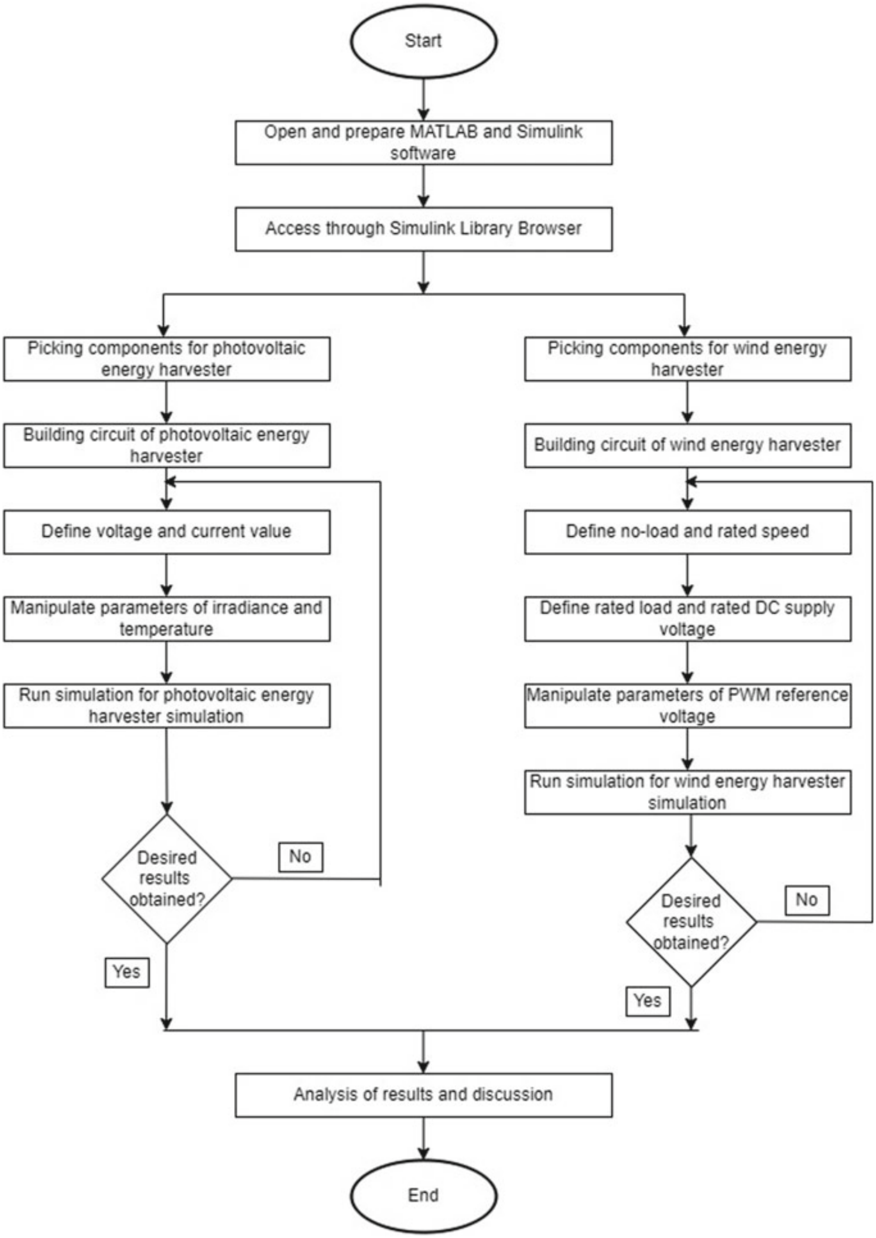

Fig. 1 Flowchart for MATLAB simulation of energy harvesting system

The renewable hybrid energy harvesting system can be simulated using MATLAB. MATLAB is a programming software designed for scientists and engineers to design, simulate, and analyze systems. It contains another add-on software called Simulink which is a graphical programming environment for modeling and simulating that will be used for this project.

Simulink is important software that can do modeling, coding, simulation, and analysis at the same time. It has a user-friendly interface that is easy to navigate and has modern look compared to other software. Simulink also provides a wide variety of hardware components and libraries that can be accessed and used for this project. Photovoltaic, piezoelectric, and wind energy can be designed with the libraries provided and simulated at the same time. Moreover, it can run large-scale simulations without a problem.

Simulink also can pinpoint the error made in the design and help the user by providing a guide. The results of the simulation can be represented in two ways which are graph and number. Users can control the output and results by altering the parameters in the model design. This versatility gives freedom to the user to modify the design and result as the user wanted in Simulink.

2.2 Prototype of Hybrid Renewable Energy Harvesting System

Figure 2 shows the process flowchart for the hardware prototype for this research work. It is divided into three parts, which are a photovoltaic energy harvester, a piezoelectric energy harvester, and a wind energy harvester.

For the hardware prototype, three renewable energy harvesters will be used which are photovoltaic, wind energy, and piezoelectric. The three renewable energy harvesters will be connected in parallel to the energy storage. The INA219 sensor module is integrated into each of the renewable energy harvesters to measure the current and voltage output of the energy harvesters. The piezoelectric utilized rectifier because the output current is in AC. Each of the sensor modules will send the information to Arduino Uno to display the information through an LCD monitor.

On the other hand, the energy storage uses a lithium-ion battery with TP4056 module integration. The TP4056 is important to charge and protect the battery during and after the charging is completed. At the same time, the battery with TP4056 will also manage to power up the Arduino Uno. Then, the power will go battery and to the load directly. Figure 3 shows the overall block diagram for the hybrid renewable energy harvesting system prototype. Figure 4 shows the prototype circuit of the hybrid renewable energy harvesting system, while Fig. 5 shows the actual representation of similar flow components.

Fig. 2 Flowchart for the hardware of the energy harvesting system prototype

3 Results and Discussion

The circuit was tested individually to show the output results for each renewable energy harvester. The results consist of the output values of the simulation such as current, voltage, power output, and energy. The parameters of the circuit are changing to show that the circuit is working as intended with certain specifications. The specification of both energy harvesters was made close to the hardware of the

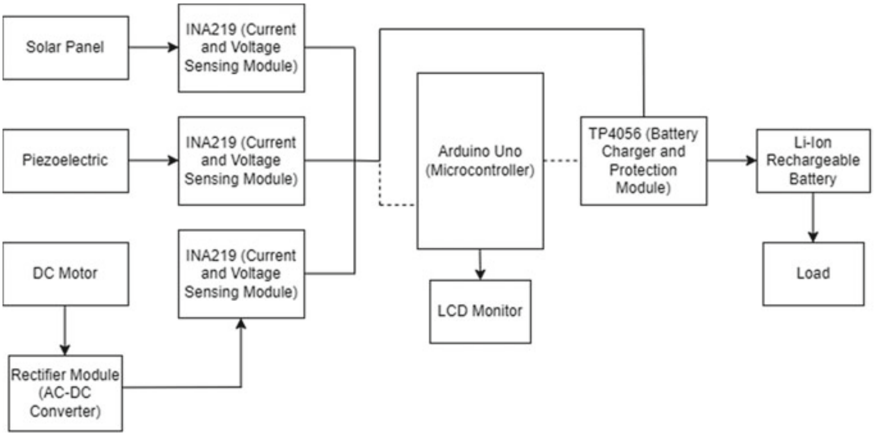

Fig. 3 Block diagram for the prototype of a hybrid renewable energy harvesting system

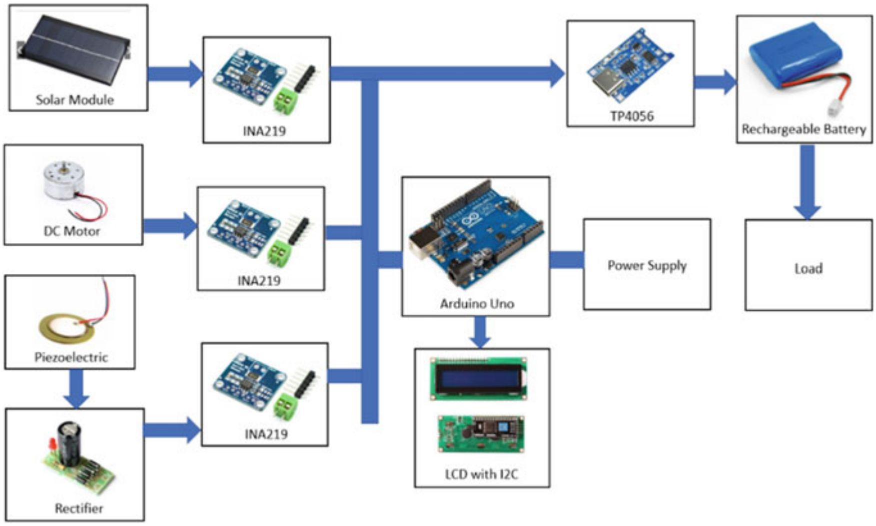

Fig. 4 Conceptual design of the actual project prototype

prototype. Figures 6 and 7 show the circuit for simulation of the photovoltaic energy harvester and wind energy harvester, respectively.

The results of the hardware prototype of photovoltaic, piezoelectric, and wind energy harvesters are also shown and discussed. For photovoltaics, the results of the hardware prototype were compared with the simulation based on the irradiance. The three-day results for photovoltaics were also compared with each other to show the effect of weather conditions.

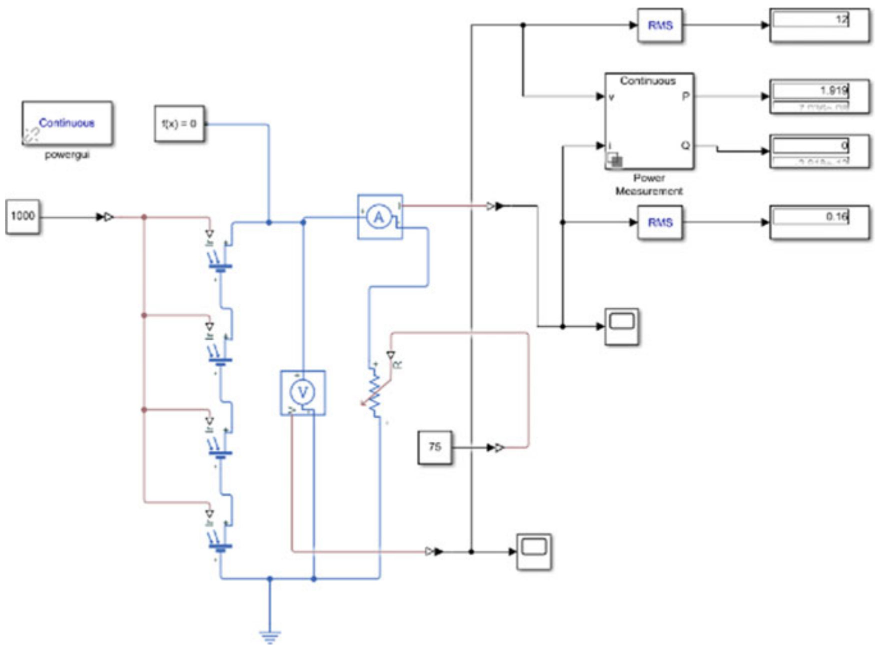

Fig. 5 Circuit for simulation of photovoltaic energy harvester

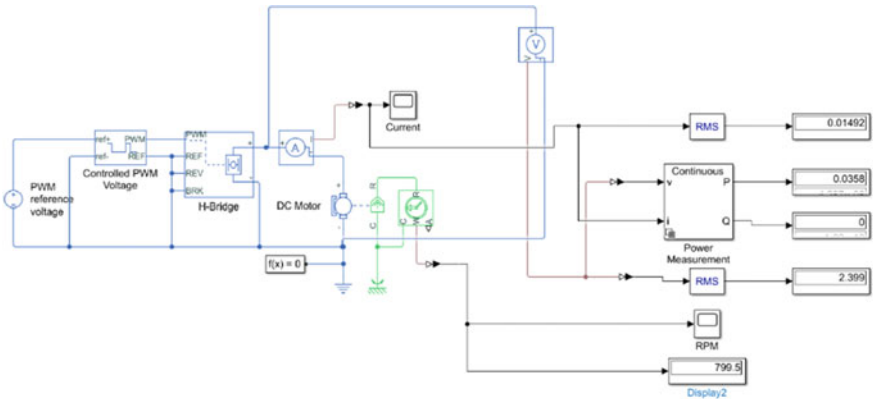

Fig. 6 Circuit for simulation of wind energy harvester

For the piezoelectric energy harvester, different mass of pressure was applied on the piezoelectric plate for 10 s with an interval of 1 s for each pressure. The result for each different mass was compared with each other. For the wind energy harvester, the results of the hardware prototype were compared with the simulation based on the RPM of the DC motor. After that, all the hardware prototype results are combined to show the continuity of the hybrid renewable energy harvester to continue harvesting

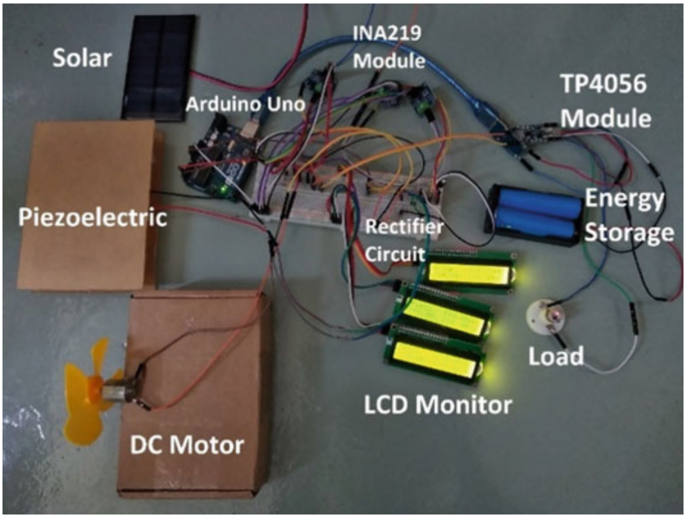

Fig. 7 Completed circuit for the prototype of the hybrid renewable energy harvester

energy throughout the day. Figure 7 shows the completed circuit for the prototype of the renewable energy harvester.

3.1 Simulation Results of Photovoltaic Energy Harvester

The results for photovoltaic simulations are shown in Tables 1 and 2. For this photovoltaic simulation, two simulations were run with different parameters setting. The first simulation ran with fixed temperature and the second simulation ran with fixed irradiance. Two parameters can change the output of the photovoltaic which are irradiance and temperature.

Table 1 shows the first photovoltaic simulation with a fixed temperature of 25 °C. It is found that when the irradiance decreases, the power output also decreases. This

Table 1 Results of photovoltaic energy harvester simulation with fixed temperature

Irradiance (W/m^2)	Temperature (°C)	Current (A)	Voltage (V)	Power Output (W)	Energy (Wh)
1000	25	0.0800	6.000	0.4797	1726.92
800	25	0.0795	5.964	0.4742	1707.12
600	25	0.0789	5.918	0.4670	1681.20
400	25	0.0781	5.855	0.4570	1645.20
200	25	0.0766	5.744	0.4399	1583.64

Table 2 Result of photovoltaic energy harvester simulation with fixed irradiance

Temperature (°C)	Irradiance (W/m^2)	Current (A)	Voltage (V)	Power Output (W)	Energy (Wh)
25	500	0.0785	5.890	0.4625	1665.00
30	500	0.0783	5.869	0.4593	1653.48
35	500	0.0780	5.849	0.4562	1642.32
40	500	0.0777	5.830	0.4532	1631.52
45	500	0.0774	5.812	0.4504	1621.44

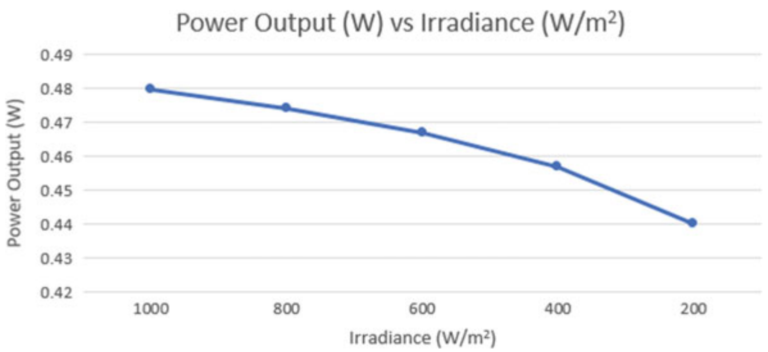

Fig. 8 Graph of power output versus irradiance for photovoltaic energy harvester simulation

shows that when there is more radiant energy, it will create more output power. Irradiance directly affects the performance of solar cells. Figure 8 shows the downward trends of power output when the irradiance is decreased.

Table 2 shows the second photovoltaic simulation with fixed irradiance of 500 W/m^2. It is found that when the temperature increases, the power output also decreases. The other parameters such as current and voltage are also decreasing. This shows that when the temperature of the solar cells increases, the solar panel efficiency is declining. Figure 9 shows the downward trends of power output when the temperature is increased.

3.2 Simulation Results of Wind Energy Harvester

To simulate the wind speed hitting the wind turbine, the PWM reference voltage is used as a variable value. When the PWM reference voltage increases, the turbine rotation is also increasing. Other than that, the other parameters such as current, voltage, and power output are also increasing as the turbine rotates faster. The power output is very small because it follows the small DC motor model with the lower

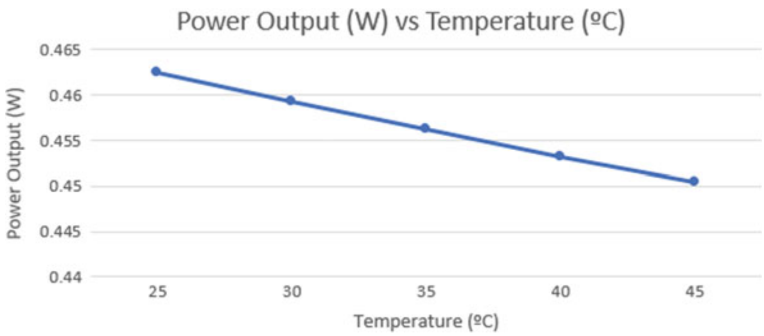

Fig. 9 Graph of power output versus temperature for photovoltaic energy harvester simulation

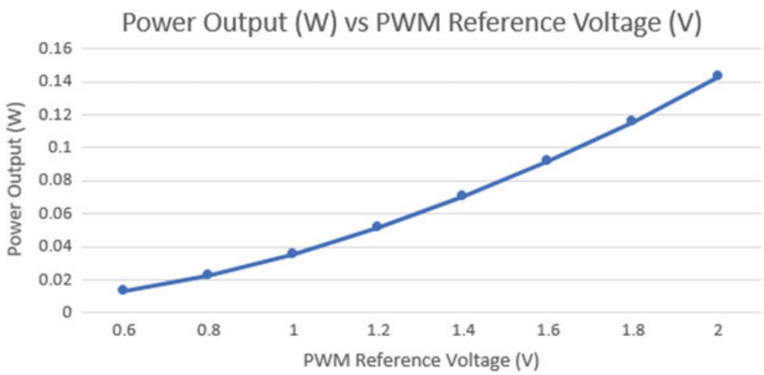

Fig. 10 Graph of power output versus PWM reference voltage for wind energy harvester simulation

specification that is used for the prototype. Figure 10 shows the upward trends of power output when the PWM reference voltage is increased.

3.3 Prototype Results of Photovoltaic Energy Harvester

For the prototype result of the photovoltaic energy harvester, the data collection was done for three days from 16/05/2022 until 18/05/2022. Each day had different weather conditions, which were cloudy, rainy, and sunny, respectively. For each day, the duration of data collection was from 07:00 a.m. until 6:30 p.m. which referred to the Solcast website's active time.

As shown in Fig. 11, power output peaked two times at around 1230 and 1500 h. That is when the weather gets sunny, the sun irradiance peaks during that time. There is a dip in power output at around 1330 h when the weather gets very cloudy, so the sun irradiance cannot reach the solar panel at full coverage.

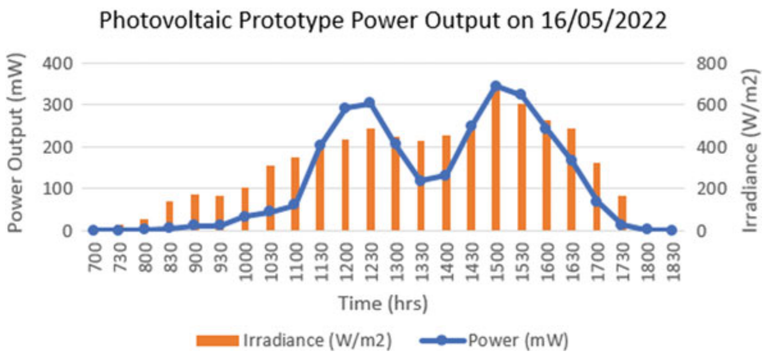

Fig. 11 Graph of power output from photovoltaic energy harvester prototype on 16/05/2022

The graph also shows that the irradiance correlates with the power output of the solar panel. The average irradiance for 16/05/2022 was 306.670W/m^2. The peak output power was at 345.210 mW which gives around 1242.760 Wh of energy, and it happened at 1500 h with 675.000 W/m^2 irradiance. The average output power that was generated was 117.525 mW for an entire day, and the average energy produced was 423.092 Wh.

Figure 12 shows that power output peaked two times at around 1030 and 1530 h. The weather was still cloudy, but there was enough irradiance that made the power output peak during that time. There is a massive drop in power output and irradiance at around 1200 h due to dark clouds and rain. The condition continued until 1430 h when the rain stopped.

On 17/05/2022, the average irradiance for on was 246.750 W/m^2. The peak output power was at 108.420 mW which gives around 390.300 Wh of energy, and it happened at around 1100 h with 588.000 W/m^2 irradiance, an hour before it started raining. The

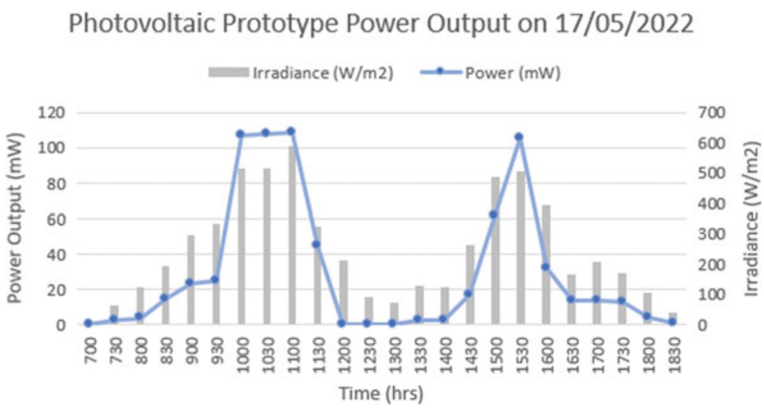

Fig. 12 Graph of power output from photovoltaic energy harvester prototype on 17/05/2022

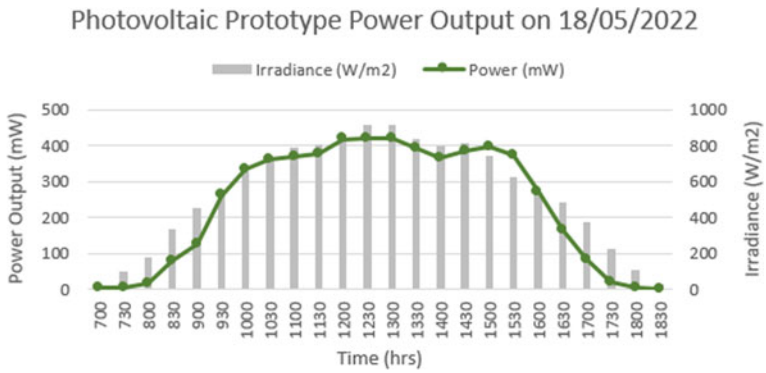

Fig. 13 Graph of power output from photovoltaic energy harvester prototype on 18/05/2022

average output power generated was 29.217 mW for an entire day, and the average energy produced was 105.181 Wh.

As shown in Fig. 13, the power output was consistent throughout the day according to the irradiance of the sun. The irradiance given stayed above 600 W/m^2 from 1100 to 1600 h and only went down slowly when the sun was also going down.

The average irradiance on 18/05/2022 was 537.875 W/m^2. The peak output power was at 421.200 mW which gives around 1516.320 Wh of energy, and it happened at 1230 h with 918.000 W/m^2 irradiance. The average output power that was generated was 235.141 mW for an entire day, and the average energy produced was 846.508 Wh.

3.4 Prototype Results of Piezoelectric Energy Harvester

For the prototype result of the photovoltaic energy harvester, the data collection was done by applying different amounts of mass on the piezoelectric plate. Three people with each different masses of 50, 55, and 60 kg step on the piezoelectric plate, respectively. The amount of voltage, current, power, and energy was recorded.

The obtained data show that the output parameters of piezoelectric energy when people with a mass of 50 kg applied the pressure on the piezoelectric plate by stepping on it for 10 s.

As shown in Fig. 14, the output power when 50 kg of mass was applied is fluctuating every second. The peak power output was 0.760 mW which gives around 2.740 Wh of energy. The average power output produced for 10 s is 0.431 mW, and the average energy produced is 1.551 Wh.

Figure 15 shows the output power when 55 kg of mass was applied is fluctuating every second. The peak power output was 0.890 mW which gives around 3.210 Wh of energy. The average power output produced for 10 s is 0.476 mW, and the average energy produced is 1.715 Wh.

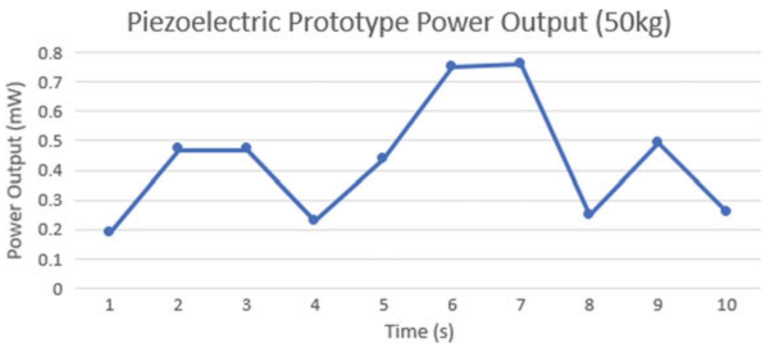

Fig. 14 Graph of power output from piezoelectric energy harvester prototype with 50 kg pressure

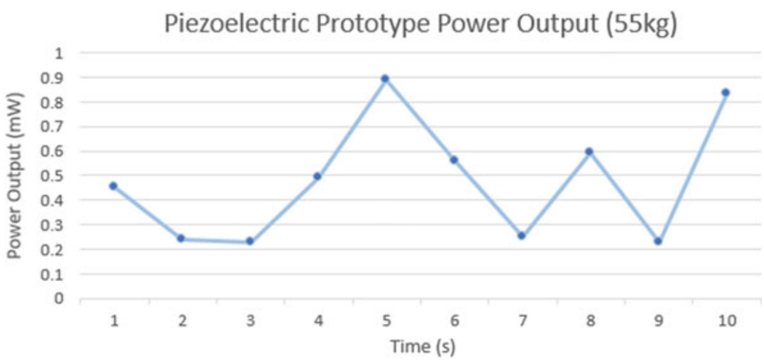

Fig. 15 Graph of power output from piezoelectric energy harvester prototype with 55 kg pressure

Figure 16 shows the output power when 60 kg of mass was applied is fluctuating every second. The peak power output was 0.940 mW which gives around 3.370 Wh of energy. The average power output produced for 10 s is 0.574 mW, and the average energy produced is 2.064 Wh.

3.5 Prototype Results of Wind Energy Harvester

For the prototype result of the wind energy harvester, the data collection was done for 3 days from 16/05/2022 until 18/05/2022. The collection of data was done every 3 h for three days straight. The wind speed data was referred to the windy website. During this day, the wind is not too strong from early morning until night. There is a spike of high wind speed at around 0800 h with 10 km/h wind speed.

Figure 17 shows the power output peaked one time at around 0800 h. The wind speed is decreasing in the next 6 h until 1400 h, and thus, the output power is also

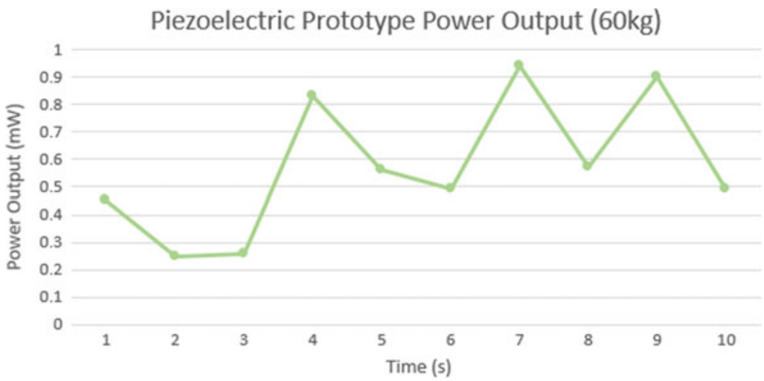

Fig. 16 Graph of power output from piezoelectric energy harvester prototype with 60 kg pressure

decreasing. From 1700 h until 2300 h, the wind is at a constant 3 km/h which also gives constant power output at around 0.040 mW.

On 16/05/2022, the average wind speed was 4.875 km/h throughout the day. The peak output power was at 0.627 mW which gives around 2.257 Wh of energy, and it happened at around 0800 h with 10 km/h wind speed. The average output power that was generated was 0.180 mW for an entire day, and the average energy produced was 0.649 Wh.

Figure 18 shows the power output peaked two times at around 1400 and 2300 h. The first peak at 1400 h had a wind speed of 13 km/h, which is the highest throughout the day, and it gives a peak power output of 0.952 mW with a peak energy of 3.427 Wh. The second peak at 2300 h has a wind speed of 8 km/h, and it gives a power output of 0.408 mW with an energy of 1.469 Wh. At the other time, the wind speed is averaging between 3 and 4 km/h and gives around 0.070 mW of power output.

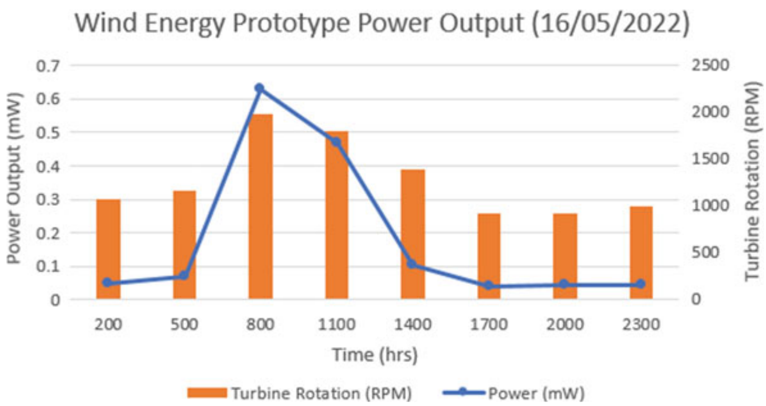

Fig. 17 Graph of power output from wind energy harvester prototype on 16/05/2022

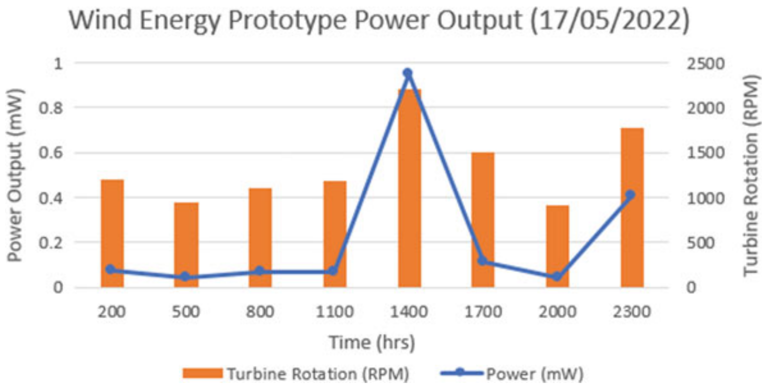

Fig. 18 Graph of power output from wind energy harvester prototype on 17/05/2022

On 17/05/2022, the average wind speed was 5.625 km/h throughout the day. The average output power that was generated was 0.221 mW for an entire day, and the average energy produced was 0.795 Wh.

Figure 19 shows that no significant peak power output is outstanding since it is almost the same. However, there is little power output peaking two times at around 0800 and 1700 h. The first small peak at 0800 h is the second highest, which gave power output of 0.108 mW and 0.389 Wh energy. The second small peak occurred at 1700 h is the highest throughout the day, which gave power output of 0.116 mW and 0.418 Wh energy. At the other time, the wind speed is averaging between 3 and 4 km/h and gives around 0.070 mW of power output.

On 18/05/2022, the average wind speed was 3.875 km/h throughout the day. The average output power generated was 0.069 mW for an entire day, and the average energy produced was 0.2484 Wh.

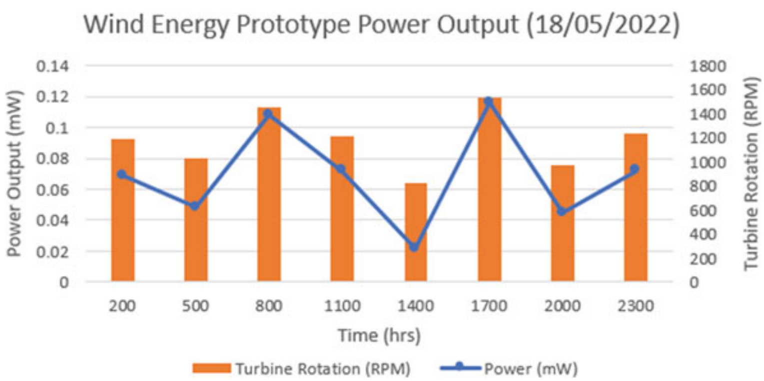

Fig. 19 Graph of power output from wind energy harvester prototype on 18/05/2022

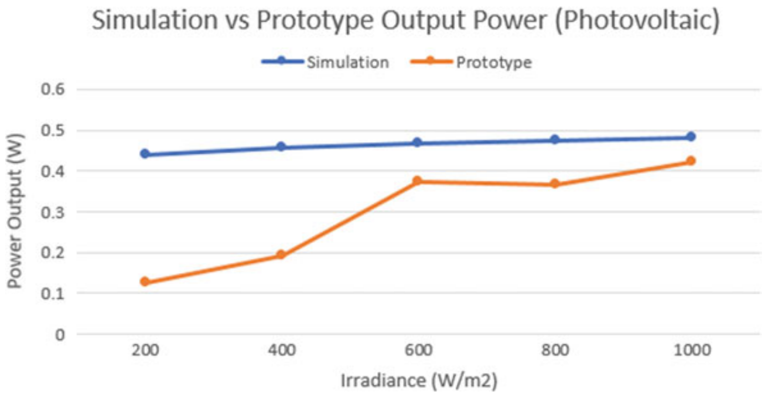

Fig. 20 Comparison between simulation and hardware results for photovoltaic energy harvester

3.6 Results Comparison of Photovoltaic Energy Harvester

Figure 20 shows that there are slight differences in power output against the irradiance for simulation and prototype. The value of power output for the prototype was taken by calculating the average power output of a certain value of irradiance from all the results.

At 200 W/m^2, the prototype has lower power output than the simulation where it dropped below 0.1244 mW compared to 0.4399 mW. The value of power output for the prototype becomes closer to the simulation starting from 600 W/m^2, where the power output is 0.3725 mW compared to 0.4670 mW at simulation. Continuing toward 800 and 1000 W/m^2, the value of power output becomes stable and constant like the simulation even though it is slightly lower. At 1000 W/m^2, there is a difference of 0.0580 mW between the simulation and prototype power output. From the comparison below, it is seen that the behavior of the prototype photovoltaic panel is that it is not very sensitive to the light at lower irradiance; hence, it generated low-power output. The photovoltaic panel worked more efficiently at higher irradiance value.

Figure 21 shows the comparison of power output for the prototype of a photovoltaic energy harvester for a three-day period which all have different weather conditions. The three weather conditions were cloudy, rainy, and sunny, respectively.

On 16/05/2022, it had the second-highest average power output at 117.53 mW and 423.00 Wh energy with an unstable pattern on the graph. Meanwhile, on 17/05/2022, it had the lowest average power output at 29.22 mW and 105.18 Wh energy. The pattern of the graph stayed at the below part, indicating that there is almost no irradiance to generate power output. Lastly, on 18/05/2022, it had the highest average power output with 235.15 mW and 846.51 Wh energy. The pattern of the graph is stable throughout the day indicating that it continuously gets irradiance and generates high-power output. From this comparison, it can be said that rainy days

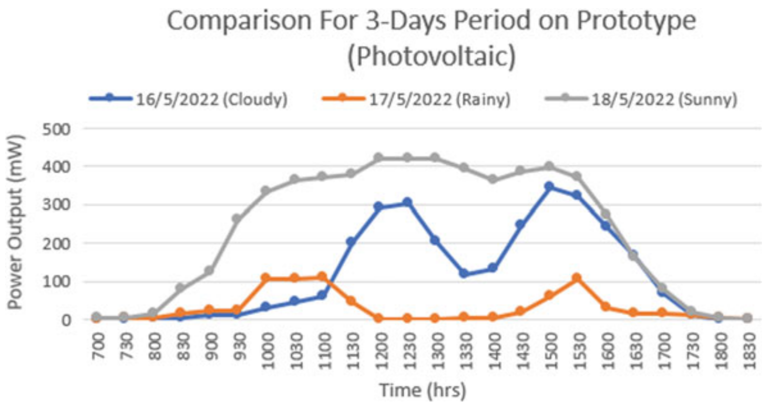

Fig. 21 Photovoltaic energy harvester output power comparison for three days

produced less power output due to low irradiance and sunny days had a higher power output due to high irradiance.

4 Conclusion

The circuit for the simulation and hardware prototype of the hybrid renewable energy harvesting system was successfully created. In this work, the simulation of a hybrid renewable energy harvesting system, consisting of a photovoltaic and wind energy harvesting system. The hardware prototype consisting of a photovoltaic, piezoelectric, and wind energy harvesting system.

The results revealed that the photovoltaic energy harvester can harvest energy from 0700 to 1830 h. The piezoelectric energy harvester can harvest energy from 0700 to 2200 h, and the wind energy harvester can harvest energy for 24 h. Based on the time, the hybrid renewable energy harvesting system can always harvest energy continuously.

The performance of hybrid renewable energy harvester vary depending on different conditions and parameters. Photovoltaic energy harvesters can harvest energy optimally on a sunny day with high irradiance. Piezoelectric energy harvesters can harvest more energy with higher mass, and wind energy harvesters can harvest energy on a rainy day with the windier conditions. Based on the performance of three energy harvesters, the photovoltaic energy harvester has the biggest potential to generate large power output. Piezoelectric and wind energy are not feasible to utilize since the power generated is less than 1–2% of the overall power generation.

Overall, there is a potential for improvement of overall output power generation for hybrid renewable energy harvesters on a larger scale.

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