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Hybrid Solar-Rainwater Harvesting System for Small Agriculture Uses

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Abstract

This project explores a hybrid renewable energy system designed for small-scale agricultural use, combining solar photovoltaic (PV) technology with a rainwater harvesting-based micro-hydropower setup. In Malaysia, solar energy is plentiful, but it also depends on weather conditions. Rainfall is abundant, but mostly unexploited for energy. The system utilises a 20W solar panel, a 12V micro-hydro turbine that produces a maximum of 12V, 0.22A, and produces about 2.64W, a 12V 5Ah battery, and an Arduino-controlled automatic system. Testing shows that during peak sunlight hours from 10:00 a.m. to 12:00 p.m., the solar panel generates 17.21V to 18.68V with currents of 0.75A to 1.05A, charging the battery from 10.13V to 11.94V over two hours. The micro-hydro system reliably delivers a steady 12V output at 0.21A to 0.22A, raising the battery voltage from 10.07V to 10.45V in two hours, with an estimated full charge time of about 19.3 hours. Temperature studies indicated that the panel reached up to 61.2°C under direct sunlight, causing the voltage to drop to 16.67V. After adding rainwater cooling, the panel temperature dropped to around 29°C to 35°C, which improved the voltage by roughly 1V and enhanced stability. Overall, the results show that solar power is the main energy source, with the rainwater-driven micro-hydro turbine serving as an effective backup and cooling system. This combination boosts the reliability and sustainability of energy supply for small farms in tropical regions.

1. Introduction

The global demand for energy is increasing, in addition to the urgent requirement to reduce greenhouse gas emissions, which has driven the interest in renewable energy solutions. Solar energy is one of the most widely used renewable energy sources because of its reliability, availability and environmental benefits. In Malaysia, the tropical environment provides plenty of solar irradiation, making the solar photovoltaic system a popular choice for energy generation. However, the solar energy reliability is highly depended on the weather condition and daylight availability, especially during cloudy, rainy or night time hours which solar irradiation is low. Although, hydropower also is reliable renewable energy source but common large scale hydropower system required massive infrastructure and natural water source which are not practical for small and remote applications. Malaysia also receives high rainfall every year which creating great potential for rainwater harvesting system that are usually underutilized for energy generation. As a result, combining the solar energy with rainwater harvesting create ideal opportunity to improve energy stability and sustainability, especially for small scale agriculture application which require continuous power supply.

1.1 Problem Statement and Objective

Malaysia electricity generation sector continues to rely heavily on fossil fuels, mainly coal and natural gas which are major contribution to greenhouse gas emissions and environmental harm [1]. Although national renewable energy targets have been created to expand renewable energy capacity and reduce emissions intensity [2], progress is slowed by the limits of current renewable energy systems. Even in solar energy is plentiful, it is become unstable and cannot provide continuous electricity during poor weather conditions. Wind energy is also not an ideal option in Malaysia since wind speeds are low and unpredictable which resulted in falling below economically acceptable standards [3]. While hybrid renewable energy system combining solar with wind have been widely studied, the application of rainwater harvesting as a secondary energy source is generally understudied despite Malaysia have high rainfall every year of around 2,500 mm [4]. Present research rarely studies the combination of solar PV systems with rainwater driven micro hydropower in small scale agriculture. If this lack is not addressed, small agricultural users will continue to have insufficient energy supplies and rely on conventional power sources. On the other hand, addressing this gap may result in more reliable, sustainable and environmental energy supply for tropical climates.

Based on identified issues and gaps, this study aims to fulfil the following objectives. The first aim of this study is to investigate the integration of solar energy systems with rainwater harvesting systems to develop a hybrid renewable energy system. The second aim of this study is to design a hybrid renewable energy system that will use the harvested rainwater to create a cooling effect on the solar panel to improve its performance. The third aim of this study is to assess the effect of temperature on the output voltage and current of the solar panel during the battery charging process.

1.2 Literature Review

Hybrid renewable power systems have gained much attention for their potential in providing an alternative solution to the growing demands for energy globally. Furthermore, hybrid power systems that include the integration of at least two different renewable power sources are capable of addressing the limitations of standalone power systems. Due to the beneficial nature of the operating conditions, hybrid power solutions that combine solar electricity with other hydro based solutions such as rainwater harvesting have shown to be quite effective.

Several studies have determined the viability and performance of solar and hydro combination systems. Suripto et al. designed a closed-loop system of solar and hydro, incorporating a back-flow water system [5], and this brought down the overall power variability while achieving a combined power output of 850W under varying climatic conditions. Furthermore, Z. A. Afif et al. constructed a pico-hydro and solar PV system based on rural Malaysian environments [6], demonstrating the proposed system reliable voltage stability as well as improved energy performance. Rajesh et al. designed a system integrating floating solar PV and micro-hydropower [7], evaluating the potential of sustaining water head using solar-assisted pumping to promote perpetual hydropower production and reduce reliance on traditional energy resources.

Other research, on the other hand, looked into the usage of water and energy at a smaller scale. Siti Nur Afiqah designed an aquaponic system powered by rainwater harvesting for domestic use at UTHM [8], illustrating the feasibility of rainwater harvesting at the local scale. At the same time, another study by Nurul Amirah designed an aquaponic system powered by an innovative switching system for both solar and hydro [9], which functioned continuously with low power consumption. Though both studies are applied for different purposes, all suggest the feasibility of combining solar power and rainwater harvesting systems.

2. Methodology

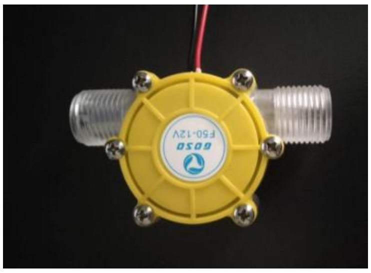
This section presents the methodology used to design, develop and evaluate the hybrid solar-rainwater harvesting system for small scale agricultural applications. The methodology contains the materials used, system operating flow, system architecture, experimental characterization and data analysis methods. An experimental method was used to evaluate the performance and functionality of the proposed hybrid renewable energy system.

2.1 Material

The material that was used in this project consist of the hardware component, electronic sensors, control device and software tools needed to build and operate a hybrid renewable energy system. The main energy source was a polycrystalline solar photovoltaic panel rated at 20 W. During times of low solar irradiation, a micro hydro turbine powered by rainwater was used as a secondary source of energy. A 12 V rechargeable battery was used for energy storage with a PWM solar charger controller regulating battery charging and preventing overcharging or deep discharge. A DC-DC buck converter was used to step down the voltage for low power components.

The control system was created using an Arduino Uno microcontroller which processed data from multiple sensors and managed system functioning. The system sensors include a voltage sensor to monitor the solar panel, a DS18B20 temperature sensor to measure the temperature of the solar panel and an HC-SR04 ultrasonic sensor to detect the level of water in the storage tank. Others component includes SPDT relays for power switching, a servo motor to operate the water valve and submersible water pumps for water circulation. Software development and programming were carried out using the Arduino IDE.

(a)



(b)

Fig. 1 (a) Solar panel (b) Micro hydro turbine

2.2 Project System Flowchart

The flowchart shows the entire operation and control logic of a hybrid solar-rainwater harvesting system. The Arduino microcontroller and sensor modules must be set up before the system can operate. The voltage and temperature sensors constantly check the solar panel output and operating temperature, while the water level sensor detects the level of rainwater in the storage tank. If measurements of solar voltage and temperature are within the preset thresholds, the system functions in solar only mode which flowing electricity straight to the load and charging the battery. When the solar panel temperature exceeds the set limit or when the solar voltage falls below the threshold due to cloudy weather or rain, the control unit controls the servo motor to opens the water valve. The released rainwater cools the solar panel surface and then spins the micro hydro turbine which generates additional electrical power. The generated energy is controlled and directed towards charging the battery. The system loops this process continuously to provide consistent power delivery and automated switching between energy sources based on real time sensor data.

Fig. 2 System flowchart of the project

2.3 Project Block Diagram

The block diagram shows the hybrid system physical and functional structure. The system has three major subsystems which is energy generation, control and sensing and energy storage and load management. The solar panel and the micro hydro turbine powered by rainwater contribute to the energy generation subsystem. Electrical outputs from both sources connect to charger controllers which then charge the battery. The Arduino Uno microcontroller functions as the control and sensing subsystem central component which receiving input signals from voltage, temperature and water level sensors and sending control signals to relays, pumps and servo motors. The energy storage and load management subsystem consists of a 12V battery and DC loads. SPDT relays are used to control power flow and prioritize different energy sources. The block diagram illustrates the interaction of system components and how energy and control signals are coordinated to provide reliable hybrid operation.

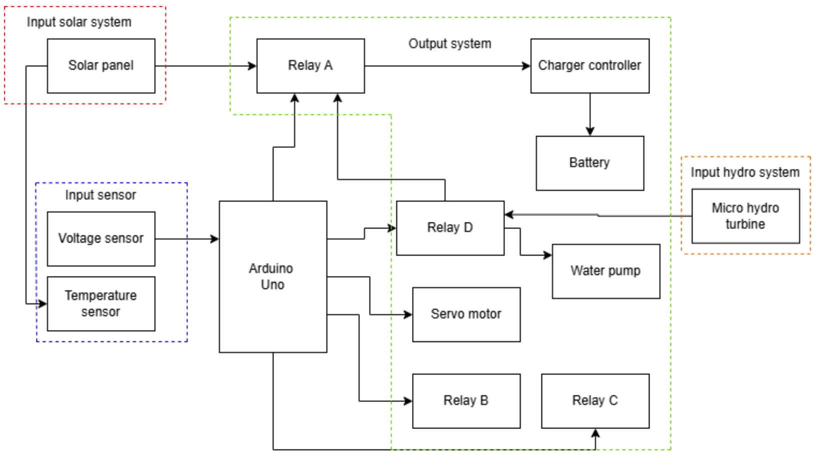


Fig. 3 System block diagram of the project

2.4 Characterization

System characterization was carried out to evaluate a hybrid energy system performance and reliability. The key performance parameters measured are solar panel voltage and current, battery voltage, micro-hydro turbine output voltage, solar panel temperature and battery charging time. Voltage and current values were measured with a digital multimeter and sensor data was processed using the Arduino serial monitor. The system operational behaviour was monitored under various conditions to ensure proper relay switching, valve operation and pump activation. The efficiency of the rainwater cooling method was determined by comparing solar panel voltage and temperature before and after water flow activation. The micro hydro turbine performance was evaluated based on its ability to generate power and charge batteries when solar energy was low. When constant power output and correct automatic responses were detected, the system was determined to be functioning properly condition.

2.5 Data Analytic Strategy

The study used a quantitative data analysis method. Voltage, current, temperature, time and charging duration were measured and compared. Numerical data were analysed to determine patterns, relationships and system behaviour under various operating environments. Graphs were used to show changes in battery charging time, solar panel temperature, voltage output and system performance. The effectiveness of the hybrid system was evaluated by comparing it to solar only and hydro assisted operation. The analysed data were used to determine if the system objectives were met and the practicality of the planned hybrid renewable energy system.

3. Results and Discussion

This section displays and discusses the experimental results achieved during the implementation and testing of the hybrid solar-rainwater harvesting system for small scale agricultural uses. The findings focus on battery charging performance, system functionality under various environmental circumstances and the impact of solar panel temperature on electrical output. The discussion clearly analyses the findings in regarding the research objectives and compares them to previous studies on hybrid renewable energy systems.

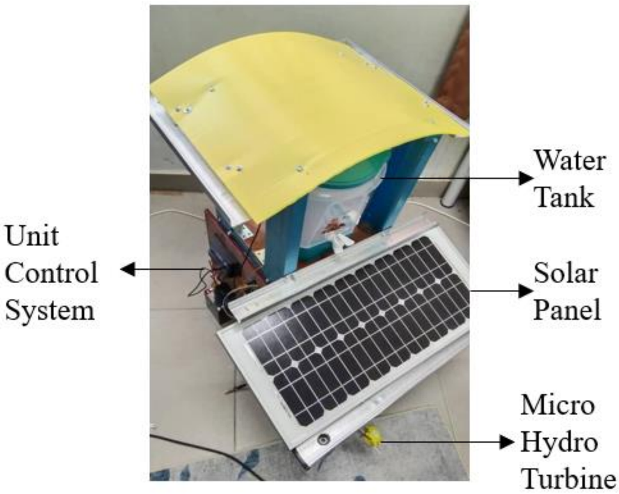


Fig. 4 Project hardware

3.1 Battery Charging Performance Using Solar Energy

Table 1 shows how long it takes to charge a 12V, 5Ah battery using a solar system during peak sunlight hours which around 10 a.m. to 12:00 p.m. The solar panel provided a relatively stable voltage range of 17.21V to 18.68V, with a maintain current of around 0.75A to 1.05A. As the charging process continued, the battery voltage gradually increased from 10.13V to 11.94V while the charging current fell slightly due to battery internal resistance and charger controller regulation.

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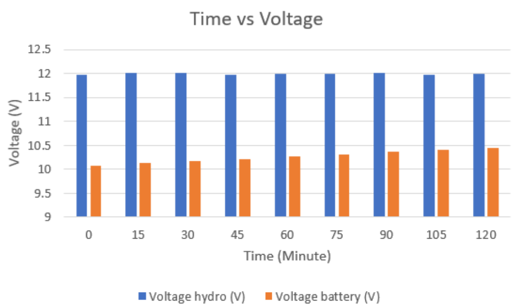
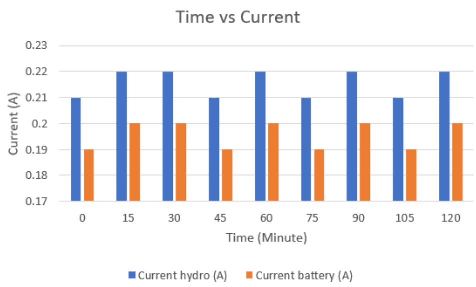
Table 1 Time taken for solar system to charge battery

Time	Voltage solar (V)	Current solar (A)	Voltage battery (V)	Current battery (A)
10:00 a.m.	17.21	0.75	10.13	0.72
10:15 a.m.	17.58	0.82	10.24	0.78
10:30 a.m.	17.82	0.88	10.43	0.83
10:45 a.m.	18.10	0.95	10.75	0.89
11:00 a.m.	18.37	1.02	10.92	0.94
11:15 a.m.	18.68	1.05	11.21	0.97
11:30 a.m.	18.52	1.02	11.46	0.95
11:45 a.m.	18.39	0.96	11.66	0.84
12:00 p.m.	18.03	0.92	11.94	0.82

This result illustrates that the solar system can efficiently charge the battery in a reasonable amount of time under ideal sunlight circumstances.



(a)



(b)

Fig. 5 Bar chart time (a) with voltage, (b) with current solar system

Figures 5 (a) and (b) show the variation of voltage and current with respect to time during the charging process of the battery using the solar energy system. The voltage level of the solar panel is almost constant throughout the time which indicating the normal operation of the solar panel. The voltage level of the battery is also increasing during the time, showing the normal operation of the solar panel and the charging of the battery. The voltage difference between the solar panel and the battery is required to ensure the flow of current through the charge controller. Considering the current, solar panel produce the current level was very high during the time which indicate that the normal and efficient operation of the solar panel. On the other hand, the current level to the battery is slightly decreasing during the time showing the normal operation of the solar energy system.

3.2 Battery Charging Performance Using Micro Hydro System

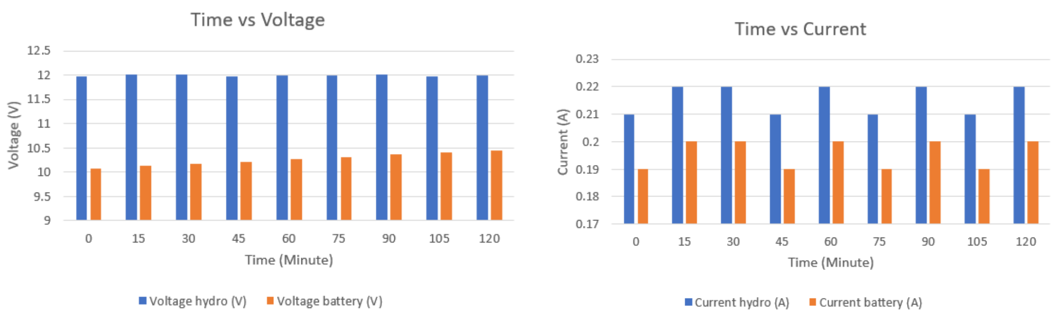
The micro-hydro turbine generated a maximum output voltage of 12V and a current of about 220 mA, producing a power output of 2.64W. Due to the low charging current, the estimated charging time for the 12V battery was 19.31 hours. Although the micro hydro unit charged at a far slower pace than the solar system, it was somehow able to deliver continuous electricity during periods of low or no solar irradiance.

$$\text{Charging time (hours)} = \frac{Battery\ Capacity\ (Ah)}{Charging\ current\ (A)} \times Efficiency\ Factor \tag{1}$$

Table 2 Time Taken for Hydro System to Charge Battery

Time (Minute)	Voltage hydro (V)	Current hydro (A)	Voltage battery (V)	Current battery (A)
0	11.98	0.21	10.07	0.19
15	12.01	0.22	10.12	0.20
30	12.01	0.22	10.17	0.20
45	11.97	0.21	10.21	0.19
60	12.00	0.22	10.26	0.20
75	11.99	0.21	10.31	0.19
90	12.01	0.22	10.36	0.20
105	11.98	0.21	10.40	0.19
120	12.00	0.22	10.45	0.20

Table 2 shows the charging performance of a 12V, 5Ah battery using the micro-hydro system over a 120 minute period. The voltage generated by the hydro system remains relatively stable at 12V, while the current varies between 0.21A and 0.22A. This indicates a consistent power supply during the charging process. As a result, the voltage of the battery increases gradually from 10.07V to 10.45V. The charging current of the battery varies between 0.19A and 0.20A, which is similar to the hydro system output current. The results indicate that the micro-hydro system can charge a battery but at a slower rate compared to the solar system.



(a) **(b)**

Fig. 6 Bar chart time (a) with voltage, (b) with current hydro system

Figures 6 (a) and (b) illustrate the change in voltage and current levels over the charging time for the micro-hydro turbine and the battery. The voltage level of the hydro turbine remains constant at 12V during the entire charging time which indicated a steady level of power generation due to the constant flow of water. At the same time, the voltage level of the battery is increasing gradually as the charging progresses. The gradual increase in the voltage level is due to the small current being supplied by the hydro turbine to the battery for charging. Looking at the current level, the hydro turbine maintains a constant current level of about 0.22A, while the charging current level for the battery remains constant at 0.19A to 0.20A which the charging current is limited by the amount of current being supplied by the hydro turbine. The results indicate that the micro-hydro system is suitable for providing constant voltage and current levels, although the low power level supplied by the hydro turbine results in a slow charging rate for the battery. This indicated that the hydro turbine is more suitable as a backup power source.

3.3 System Functionality Under Different Environmental Conditions

During peak sunlight conditions, the system effectively detected solar panel temperatures above 75°C. The temperature sensor activated the servo motor to open main water tank valve, allowing rainwater to flow across the solar panel surface. This cooling effect reduced panel temperature while increasing voltage stability. At the same time, water flow through the micro hydro turbine produced electrical power to support system functioning.

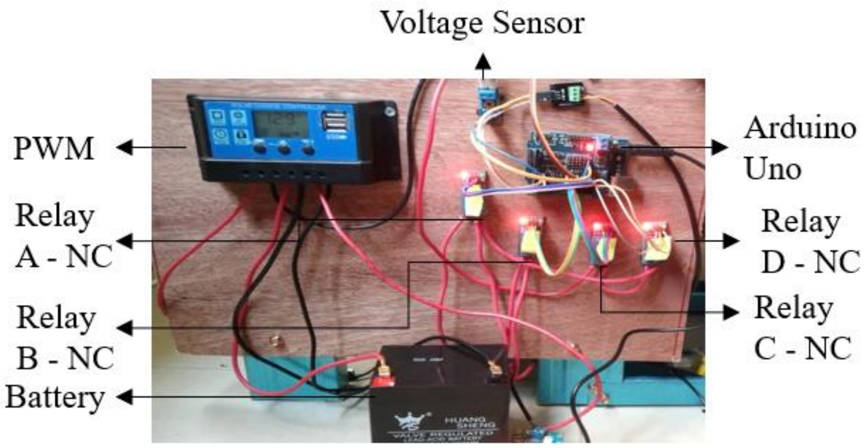


Fig. 7 Control unit system during peak sunlight

During rainy, cloudy or nighttime conditions, the voltage sensor detected little or no solar output. The control unit switched the energy source to the micro hydro system, allowing rainwater driven power generation to charge the battery and keep the system running.

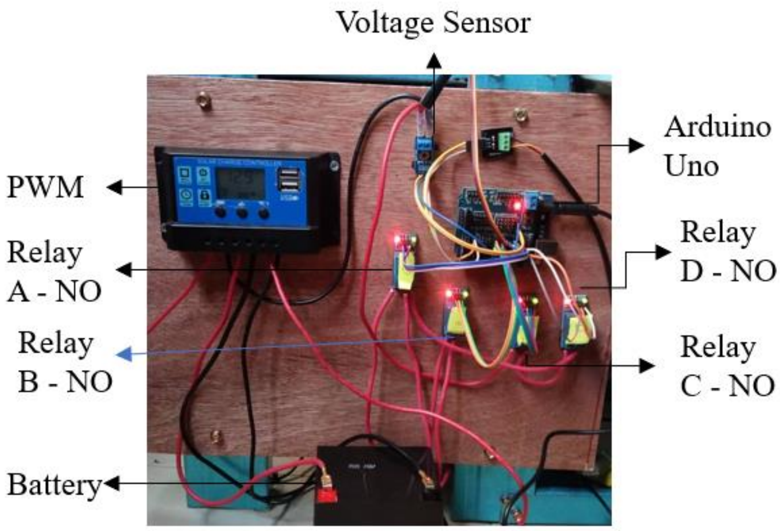


Fig. 8 Control unit system during low sunlight

3.4 Solar Panel Temperature Analysis

Table 3 displays comparison of solar panel performance characteristics measured between 10:00 AM and 2:00 PM under both before and after cooling conditions. The performance measures include solar panel temperatures, output voltage and output currents. All of these parameters are critical for assessing solar panel performance during peak sunlight hours.

Table 3 Comparison of Solar Panel Before and After Cooling

Time	Before Cooling			After Cooling		
	Temperature (°C)	**Voltage (V)**	**Current (A)**	**Temperature (°C)**	**Voltage (V)**	**Current (A)**
10:00 a.m.	44.0	20.56	0.42	28.7	21.63	0.51
11:00 a.m.	51.7	20.83	0.55	34.3	21.90	0.60
12:00 p.m.	55.0	20.29	0.46	29.3	21.47	0.50
1:00 p.m.	61.2	16.67	1.10	34.6	17.85	1.15
2:00 p.m.	56.4	17.12	1.08	32.0	18.22	1.12

Before the implementation of the cooling system, the solar panel temperature rapidly increased from morning to afternoon, reaching temperatures of up to 60°C due to continuous exposure of strong solar irradiation leading to a progressive decrease in output voltage. This behaviour is consistent with photovoltaic panels negative temperature coefficient which causes voltage degradation as operating temperature rises, while output current remains relatively constant because it is primarily influenced by irradiance rather than temperature. After the water-cooling system was applied, the solar panel temperature drastically dropped to around 35°C, resulting in an average increase of approximately 1V in output voltage over the uncooled condition. The output current varied just slightly, showing that the cooling technique improved voltage performance rather than current production. Overall, the results in Table 3 show that good thermal management through panel cooling enhances solar electrical performance by lowering voltage losses during peak operation hours.

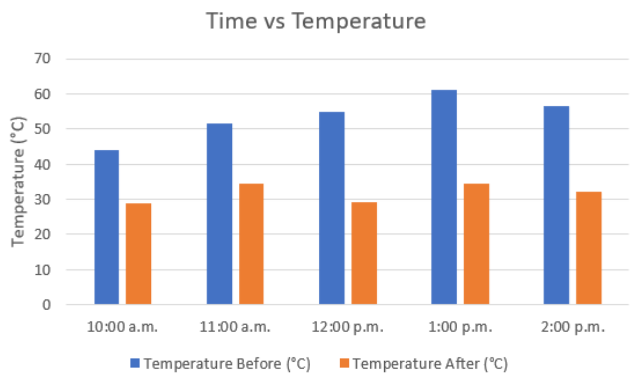
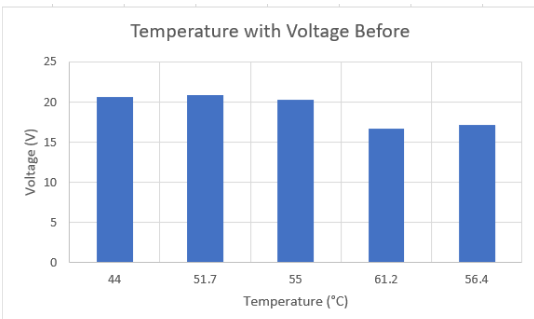
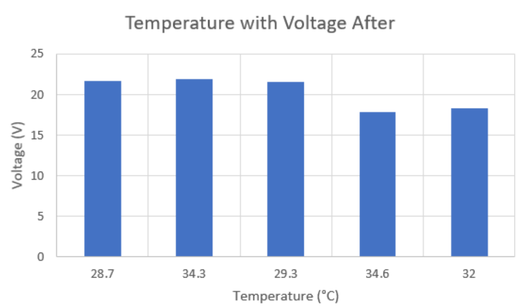


Fig 9 Bar Chart Time vs Temperature

Figure 9 displays a bar chart comparing solar panel temperature over time. The graph indicates an increase in temperature from morning to early afternoon, showing that thermal buildup takes place during peak solar hours. The highest temperature is clearly observed between 12:00 PM and 1:00 PM, which corresponds to the peak sunlight hour. This demonstrates that temperature rises with continuous sunshine exposure, which is critical for solar panels.

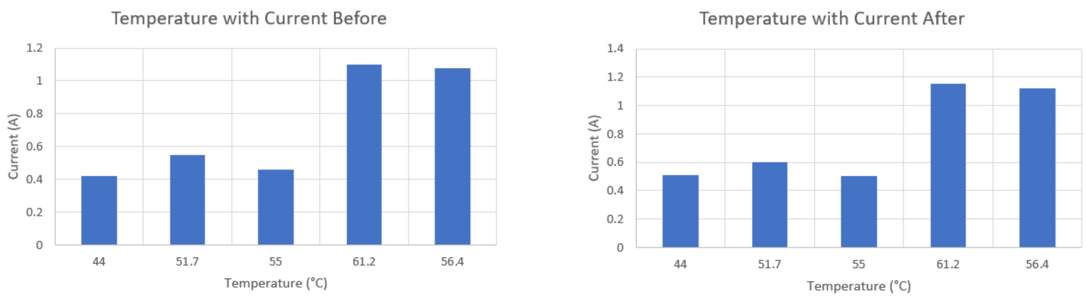




(a) **(b)**

Fig. 10 Bar chart temperature with voltage (a) before (b) after cooling

Figures 10 (a) and (b) show the relationship between solar panel temperature and output voltage before and after the introduction of the cooling system. Before cooling, an increase in solar panel temperature causes a considerable reduction in output voltage which is related to photovoltaic panel negative temperature coefficient, suggesting that excessive heat considerably affects voltage performance. After the cooling system is applied, the panel temperature is reduced to less than 35°C resulting in a greater and more stable output voltage than in the uncooled condition. This gain indicated how the cooling mechanism successfully decreases thermal stress on the solar panel, improves voltage stability and boosts total energy conversion efficiency during peak operation hours.



(a) **(b)**

Fig. 11 Bar chart temperature with current (a) before (b) after cooling

Figures 11 (a) and (b) show the relationship between solar panel temperature and output current before and after the implementation of the cooling system. Before cooling, the data reveal that changes in panel temperature do not result in a significant drop in output current. This showing that solar panel current is mainly affected by solar irradiation rather than temperature, with only small variations due to thermal effects. When the cooling system is activated, the decrease in panel temperature causes a small rise or stabilization of the output current when compared to the before cooled condition. Although the improvement in output current is less visible than the improvement in output voltage, the results show that the cooling system primarily contributes to current stability rather than significantly boosting current magnitude.

3.5 Discussion

The outcomes clearly show that the hybrid solar-rainwater harvesting system enhances energy reliability by overcoming the limitations of solar only systems. The solar charging data demonstrate that photovoltaic energy is used as the primary power source due to its higher power output and faster battery charging capability. However, the observed voltage reduction at elevated panel temperatures supports the widely acknowledged negative temperature coefficient behaviour of solar modules.

The use of rainwater-based cooling significantly reduced panel temperature and stabilized voltage output, enhancing overall system efficiency. This finding lines up with previous studies that found improved photovoltaic performance when active or passive cooling techniques were used. Unlike traditional cooling techniques, the proposed system makes use of harvested rainwater, increasing sustainability while consuming no additional energy. Although the micro hydro turbine generated less power than the solar panel, its ability to operate consistently in low-light environments proves its use as a backup energy source. The long charging time seen while utilizing the hydro system alone demonstrates its restriction as a primary power source. However, this limitation is acceptable in the context of a hybrid system where reliability takes priority over charging speed.

Rainwater harvesting is much easier when compared to the hybrid system that incorporates solar and wind power, considering the slower speed of the wind and the higher amount of rainfall that is normally prevalent in the tropical climate found in the case of Malaysia. The automatic switching system of the Arduino circuit ensures that the system is efficient since there is better accessibility to the appropriate source of power in relation to the context of the surroundings. Taking into consideration the findings obtained, there is evidence that the objectives of the research work have been achieved. An appropriate approach has been used in this research paper in order to increase the flow of energy and the sustainability point that would make the system relevant for agricultural purposes.

Conclusion

This experiment has been successful in designing and implementing the concept of a hybrid solar rainwater harvesting system on a small-scale agricultural application. By integrating a solar photovoltaic system and a rainwater-driven micro hydro turbine, the system has improved the sustainability of energy as the solar electricity in tropical regions has been proven to be unreliable in nature. Experimentation has shown that solar energy was the dominant source of energy in this system, and rainwater harvesting was successful in acting as a cooling system for the solar panels as well as generating supplementary energy during periods of reduced solar intensity.

Future research can concentrate on increasing the micro hydro turbine capacity and efficiency in an attempt to raise the production of electricity and the rate of battery charging time reduction. There are possibilities of improving the system by incorporating the use of the Internet of Things (IoT) in the project to enable control of the system's parameters in an online system. There are many aspects that can be researched in the future with the aim of promoting the use of the system in larger agricultural applications.

Acknowledgement

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