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DESIGN OF COMPREHENSIVE MONITORING ON HYBRID PHOTOVOLTAIC AND THERMOELECTRIC GENERATOR USING IoT

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ABSTRACT
The study aims to design and develop a more efficient measurement monitoring system based on influential parameters for the performance of hybrid PV and TEG modules using IoT with the Thingspeak application. The parameters measured include the PV top and bottom surface temperatures and output current and voltage, the surface temperatures of the TEG's hot and cold sides, their respective current and voltage outputs, air humidity, and solar intensity. This IoT-based monitoring system experimental method utilizes two types of PV, polycrystalline and monocrystalline, each rated at 50 Wp, in a hybrid configuration with 5 TEG modules attached to the back of the solar panel. The monitoring design results indicate that sensor measurements were accurate and data readings were reliable. The temperature difference between the two sides of the TEG was measured up to 21.7°C, and the hybrid efficiency of the monocrystalline PV with TEG showed better results compared to the polycrystalline setup, achieving optimum efficiency above 6%, with the PV surface temperature maintained at an average of 50°C. Additionally, IoT monitoring revealed the effect of air humidity on TEG performance: lower air humidity resulted in a larger ΔT, peaking at 21.7°C with humidity at 39.1%. Therefore, this study recommends using IoT technology for observational data collection on system performance, particularly for PV and TEG, with sensor component modifications tailored to the characteristics of the targeted sensor object.
Keywords: *Thingspeak-Blynk, Iot Monitoring, Hibrid PV-TEG, Measurement Sensor.*

1. Introduction

Eastern Indonesia, particularly Palu, located on the equator in the center of Sulawesi, receives high solar intensity. This level of solar radiation is ideal for harnessing renewable energy through solar panel (PV) and thermoelectric generator (TEG) technology. Since both PV and TEG have similar output modes, combining them allows the use of two sources simultaneously: sunlight and photon light at once (Piarah *et al.*, 2019)(Mustofa *et al.*, 2020)(Muhtar Kamaludin *et al.*, 2020)(Mustofa *et al.*, 2021)(Mustofa *et al.*, 2019). Integrating PV and TEG technology can enhance the total energy system efficiency because the TEG can utilize excess heat from the PV. This process helps maintain a stable PV surface temperature, promoting consistent efficiency. Installing TEG on the underside of the PV panel also acts as a cooling technique for the PV, alongside fluid circulation, which helps maintain the cold side temperature of the TEG module beneath the panel surface (Awai *et al.*, 2024). One advantage of TEGs is that they can continue to generate electricity from existing temperature differences through the Seebeck effect, even when sunlight is not optimal, such as on cloudy days or at night. This is a critical reason for integrating PV and TEG technologies, making them suitable for autonomous energy systems in remote locations or areas where the central energy infrastructure is unavailable. This setup enables a more self-sufficient and cost-effective installation in the long term.

However, it is essential to note that combining PV with TEG requires careful design to ensure the optimal integration of the two technologies. (Basri *et al.*, 2018)(Mustofa, 2022)(Qasim *et al.*, 2022)(Saleh *et al.*, 2020)(Islam, 2024). Although PV achieves much higher efficiency than TEG, TEG is more effective at generating electricity due to the temperature difference between its two modules. This integration will involve thermal management, power control, and adaptation to changing environmental conditions. Therefore, temperature, solar intensity, and surrounding air humidity monitoring systems significantly impact the technology's performance during the design phase. In general, in experiments, observations of PV-TEG output data and external factors such as light intensity, temperature, and surrounding air humidity are conducted using manual and digital measuring instruments. Testing these measuring instruments becomes less practical outdoors in direct, intense sunlight. It requires integrating wireless monitoring technology that can be observed remotely and stores data in the cloud network. The Internet of Things (IoT) technology greatly facilitates online data measurement. Its supporting components are readily available and affordable on the local market. Additionally, it provides more precise results and eliminates the need for field personnel to work under direct sunlight for extended periods to record PV-TEG output data and external parameters, except for verifying that the electronic devices are correctly connected and operational. The advantage of measuring data variables in this PV-TEG integration is increased data precision, with recordings possible at short intervals (per second) and allowing for rapid repetition if any anomalies in the readings are detected. Therefore, this research aims to design hardware and software capable of comprehensively monitoring the measurable parameters from both sources of electrical energy generation and parameters affecting system performance in outdoor environments, such as temperature, solar intensity, and air humidity. The advantage of measuring data variables in the integration of PV-TEG with IoT applications is that it increases data precision and can be recorded in adjusted time intervals and can be detected if there are any irregularities in the figures.

From the above phenomenon, preliminary investigations have been conducted by (Rahman *et al.*, 2023) and (Mustofa *et al.*, 2023) utilizing IoT technology, but limited to sensors measuring PV surface temperature, with observations restricted to a 4-hour window from 11 a.m. to 3 p.m, while PV and TEG output power data is done manually every 5 minues. Recording parameter data is necessary to capture external factors that affect system performance, especially if PV is combined with a Peltier module. In other words, the results vary due to the limitations of measurement speed and the use of manual measuring instruments in open spaces with fairly high sunlight intensity. In fact, simultaneous data accuracy is needed to obtain a complete picture of the effects of combining PV panels and TEG modules. An innovative IoT application design was also developed by (Hassan, 2020), who explained in detail in his research how PV technology is a power source for medical wearable sensor nodes capable of monitoring body temperature and heart rate on patient clothing. This setup allows doctors to monitor patient health remotely using only a smartphone. This demonstrates that IoT devices provide reliable and practical data without requiring a presence in a hospital or at the data collection site.

Therefore, this study aims to design and develop a more efficient measurement system for the combination of PV and TEG based on IoT to obtain parameters that affect system performance.

2. Literature Review

2.1 Overview of PV-TEG systems and challenges in data collection

Differences in weather conditions during data collection on combined PV panels and TEG modules in open spaces under sunny conditions, where sunlight intensity exceeds 300 W/m², are crucial for assessing system performance. Even in cloudy or rainy weather, with low or high humidity levels, the environmental temperature may still be relatively high, which affects the temperature difference across the TEG module and enables it to generate electrical energy through the Seebeck effect. On the other hand, this condition is less effective for solar panels, which rely on sunlight absorption to generate electrical energy. These differing characteristics have implications when combining PV and TEG to gather output power data and external factor variables. To address this issue, a technology operates beyond part-time and allows extended data collection periods. Implementing wireless sensors with Internet of Things (IoT) technology offers an affordable and precise solution for recording test data.

Several studies still use digital devices to record observational data on PV panels or TEG module observational data. (Halim *et al.*, 2023) investigated the effect of adding copper plates to the hot side of the Peltier module to enhance the Seebeck effect and recorded observational data with a digital multimeter from 9 am to 5 pm. Effectively, only 8 hours of data were recorded. However, additional periods outside this range could impact temperature differences in the module, limited only by the research assistant's availability to record the remaining data. (Tradacete-Ágreda *et al.*, 2024) developed IoT technology that enables PV panels to obtain electrical data and external factors, trace the I–V curve, and reconfigure their connections within the PV string. Meanwhile, research by (Nazri *et al.*, 2018)(Nazri *et al.*, 2019) and (Nazri *et al.*, 2022) combined PV and TEG within a time range from 11 am to 3:30 pm, using the forced convection heat transfer method with airflow to maintain the temperature of the cold side of the Peltier module. There are still several hours before 11 am and after 3:30 pm when sunlight is still available to facilitate electrical energy conversion from this hybrid technology. However, this requires testing with a Sun Simulator, where intensity can be adjusted. The limited observation period provides insufficient information on the performance of the design during testing.

Furthermore, (U. A & Jumaat, 2022) conducted observations of PV-TEG hybrids under rainy, cloudy, and sunny weather conditions, recording test data using a combination of LabVIEW and MATLAB on a computer, with data collection from 6 am to 8 pm. The test results indicate that the highest PV-TEG hybrid efficiency was achieved under sunny conditions at 22.66%, followed by rainy conditions at 13.27%, and the lowest under cloudy conditions at 4.53%. The data collection technique involved an Arduino microcontroller, with data analysis conducted on a computer using MATLAB. The complete data collection technique using a digital multimeter for several hybrid PV-TEG studies is well-documented by (Basri *et al.*, 2018) (Piarah *et al.*, 2019) (Saleh *et al.*, 2020) (Rousan, 2020) (Djafar *et al.*, 2021). Data collection techniques and measurement tools must adapt as technology advances toward AI.

2.2 Review of existing IoT application in PV-TEG monitoring

The IoT application was implemented in the study by (Charris *et al.*, 2020) to measure the temperature and voltage of the TEG module, a heat-absorbing plate was installed on the hot side of the module, while the temperature on the cold side was maintained using a coolant made from PCM material. Data was collected over approximately 24 hours, with a digital multimeter used as an observation tool. In further testing, (Mona *et al.*, 2022) used geothermal hot water in a special reservoir at 105°C for the module's hot side. In contrast, the cold side of the TEG was maintained by circulating low-temperature water. The power generated by the TEG was used as electrical input for the IoT system. The IoT system was connected to three sensor systems: first, a temperature sensor to measure air temperature and humidity; second, a sensor for monitoring hot and cooling water temperatures in the module; and third, a sensor to detect Sulfur Dioxide (SO_2) content. The data obtained were then displayed on a smartphone. (Manivannan *et al.*, 2022) also implemented an IoT device for temperature monitoring on a TEG and a solar collector (PVT-TEG). In another study, (Franke *et al.*, 2024) developed a new ceramic TEG module called Origami, produced via 3D printing. It can power IoT devices using low-grade waste heat. In line with IoT technology, (K. Irshad *et al.*, 2020) also developed a performance monitoring system for thermoelectric materials used in air conditioning (TEC for smart buildings) with IoT devices.

The study on combined PV-TEG simulation and hardware that implements IoT devices for measuring PV and TEG temperature was conducted by (Khatun Mishu *et al.*, 2021). The sensor device setup, shown in Figure 1, is equipped with an ESP32 interface, compatible with SPI/SDIO or I2C/UART, and connected via Bluetooth and Wi-Fi networks.

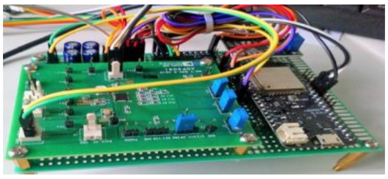


Fig. 1. IoT devices (Khatun Mishu et al., 2021)

(Pradeep *et al.*, 2020) also developed IoT technology to monitor and manage the electric energy harvested through a hybrid PV-TEG prototype. There is no information on which parameters are connected to the IoT technology; it appears limited to the PV temperature sensor and TEG module.

The research results above reveal that the application of IoT technology to obtain temperature data during PV and TEG integration testing and for environmental variables remains very limited. Therefore, further related research and development recommendations are needed.

3. Control Design of IoT

IoT is generally defined as a network of objects embedded with sensors and connected to the Internet. It is a network of physical objects, or "things," embedded with electronic devices, software, sensors, and network connectivity, enabling these objects to collect and exchange data. IoT allows objects to be sensed and controlled remotely across existing network infrastructure.

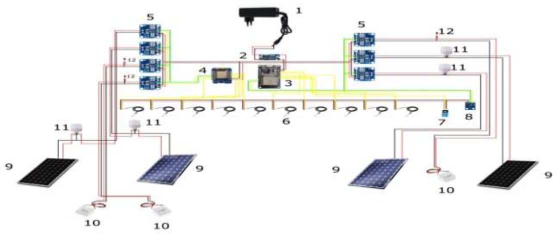
3.1 IoT platform selection

This research uses two IoT cloud platforms, blynk.io, and thingspeak.com (BTweblink), to display data from sensor operations on the hybrid PV-TEG. Thingspeak.com, as the cloud platform, displays PV and TEG current and voltage, while the blynk.io application displays temperature, humidity, and sunlight intensity parameters. To avoid impedance in the output currents of the panel and module, the series of TEG modules is not combined with the PV output power, which is much greater. The outputs of both are accumulated as hybrid power to the load. A similar approach was taken by (Khatun Mishu *et al.*, 2021), but they used a Schottky diode to prevent reverse current flow. This resulted in increased current with the parallel connection of the current sources.

3.2 Hardware components and fucntionally

The Arduino IDE transmits data via a wireless platform to BTweblink and can be monitored on a smartphone. Arduino has two types of microcontroller modules: the ESP32 module (Khatun Mishu *et al.*, 2021) and the Wemos D1 mini. The Wemos D1 mini controls five DS18B20 sensors and four INA219 sensors. Meanwhile, the ESP32 controls five DS18B20 sensors, one DHT11 sensor, one BH1750 sensor, and three INA219 sensors, which measure PV and TEG current and voltage sent to the thingspeak.com application. Temperature is measured using a DS18B20 sensor, with readings configured in the ESP32 program. Data is then sent to the blynk.io application. The DHT11 measures humidity, functioning similarly to the DS18B20, and the BH1750 sensor measures light intensity. Figure 2(a)(b) shows the Arduino device and its test connection circuit.

(a)



(b)

Fig. 2. IoT monitoring design; (a) Arduino hardware, (b) scheme of monitoring

The system includes a DC 12V power source (1) connected to a step-down module (2) that reduces the voltage from 12V to 5V for data acquisition, with an ESP32 module (3) and a Wemos D1 module (4) both transmitting data to a web server. It also uses INA219 sensors (5) for measuring PV and TEG current and voltage, DS18B20 sensors (6) for PV and TEG temperature, a DHT11 sensor (7) for humidity, and a BH1750 sensor (8) for sunlight intensity. Energy is generated by 100 Wp monocrystalline and polycrystalline PV panels (9) and TEG modules (10), with the system output displayed via a DC bulb (11) and an LED bulb (12).

3.3 Experimental setup

The test location was carried out in the Mantikulore area, Central Sulawesi, Indonesia, at Latitude -0.8882403' and longitudinal 119.892891', which placed two types of PV panels consisting of monocrystalline and polycrystalline. At the bottom of the PV panel, a circle configuration of 5 TEG modules is attached. The temperature of the cold side of the TEG SP1848 27145SA is maintained by circulating water in the heatsink fins above the module surface. This model is analogous to the research of (Rahman *et al.*, 2024), but still uses manual measurements where data is collected every 5 minutes.

Meanwhile, Fig. 3 shows the flowchart of the sensor system operating within the PV-TEG integration and BTWeblink technology, which displays sensor data readings on a smartphone. Five types of sensors measure current (Amperes), voltage (Volts), temperature, air humidity, and solar radiation intensity. The working principle is that the PV-TEG combination is connected to an electrical circuit to a microcontroller, where the reading of current-voltage and temperature data is sent to the Wifi module using ESP32, while the humidity and solar intensity data use the Wemos D1 mini microcontroller. The data is processed in Thinkspeak and Blynk to be recorded. The advantage is that the data remains stored for about a week if you don't want to analyze it directly. This is the memory capacity of the Thinkspeak and Blynk IoT platforms available. The disadvantage of these sensors is that the reading will be an error if the sensor tip does not touch the measured surface exactly. Thus, it must be checked and calibrated frequently to obtain data accuracy.

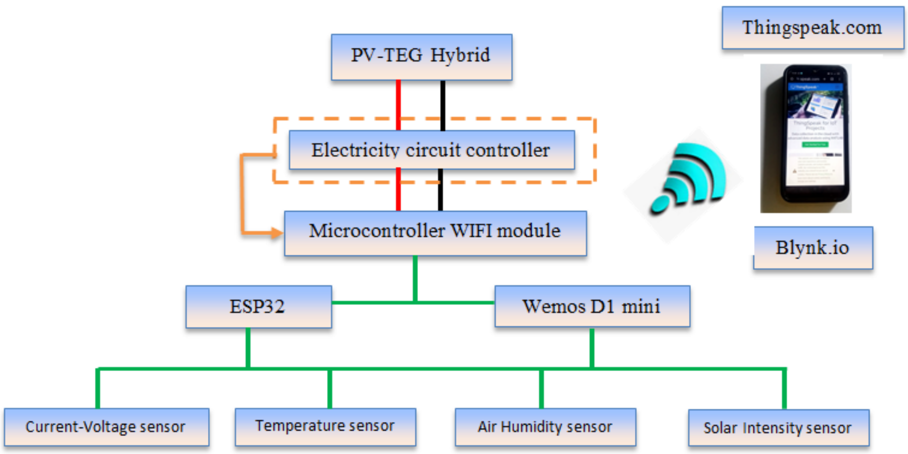


Fig. 3. Flowchart of the Sensor System in PV-TEG Hybrid

3. Results and Discussions

4.1 IoT and TEG efficiency

As shown in Fig. 4, the results demonstrate the impact of IoT technology on the performance of the TEG module. There was a significant performance increase of up to 6% in the TEG modules attached to the back of the PV at the start of the observation period. Conversely, performance gradually declined after 12 pm. This is due to the ability of polycrystalline PV materials which are not resistant to high temperatures when solar radiation also increases (Alluri et al., 2024) (Vincent, 2021). When TEG efficiency increased, air humidity reached 40% before 10 am. Furthermore, when the increase in TEG efficiency occurred, the air humidity reached 40% before 10 am. As the air humidity increased slowly, the module performance began to decrease gradually until the end of data collection at 1%. As air humidity rose slowly, the module's performance decreased gradually, reaching 1% by the end of data collection. The graph also indicates TEG efficiency is higher when attached to monocrystalline PV panels than polycrystalline panels (Rahman et al., 2024). These results suggest that the IoT application functions effectively for the Peltier module and its environment.

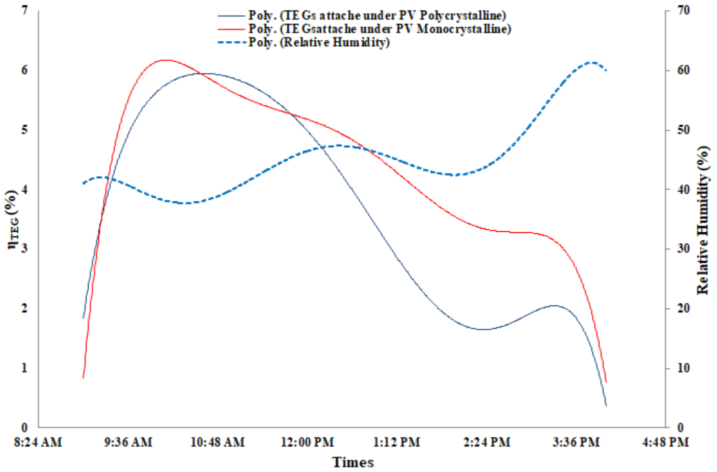


Fig. 4. Effect of Air Humidity on the Performance of TEG Hybridized with PV

The IoT application operates with normal sensitivity to solar intensity measurements, as illustrated in Fig. 5, where the characteristics differ slightly from relative humidity. The increase in TEG performance is directly proportional to the rise in solar intensity, but this effect persists until around 10:45 am. The efficiency of TEGs attached to monocrystalline PV panels is generally higher than that of polycrystalline panels, with ηTEG reaching an optimal level of 6.2% when hybridized with monocrystalline PV and 5.7% with polycrystalline PV. This indicates that the photon radiation absorbed, along with the solar thermal radiation transmitted by the monocrystalline PV to the TEG module, is greater than that of polycrystalline PV. In other words, the increase in TEG efficiency is directly proportional to PV efficiency (Islam, 2024)(Vincent, 2021) (Karakilic *et al.*, 2022) (A. S. Irshad, 2023) (Benghanem *et al.*, 2023). However, TEG performance declines sharply during the time interval from 10:45 am to around 2:00 pm. A notable change occurs after 3:00 pm when module efficiency decreases significantly alongside the drop in solar intensity toward late afternoon. This phenomenon might explain why data collection was halted at 3:30 pm in the study by (Nazri *et al.*, 2018).

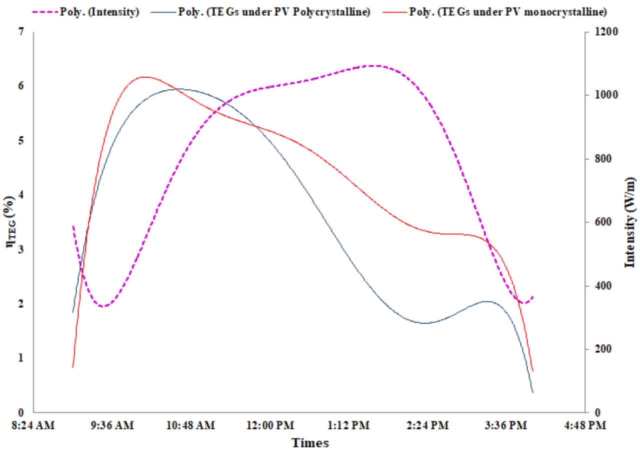


Fig. 5. Effect of Solar Intensity on the Performance of PV-Hybridized TEG Modules

From the above observations, it can be concluded that relative humidity affects the increase in TEG module efficiency until around noon, approximately at 12 pm. However, its impact is not as significant as increased solar intensity. The two figures above indicate a significant temperature difference (±6°C) on both sides of the TEG module at the start of the observation period, lasting until around 11:00 am. This is likely due to the operational temperature difference specification of the TEG SP1848 27145SA material, which can reach up to 100°C, and the module's cooling rate (Jaziri *et al.*, 2020)(Liu *et al.*, 2024).

Fig. 6 further demonstrates that, although relatively minor, air humidity does influence the temperature difference between both sides of the TEG module. The lower the air humidity, the greater the ΔT of the TEG, peaking at 21°C with a humidity level of 39.1%. When humidity increased to 46.5%, the temperature difference in the module dropped to 18.9°C and continued to decrease until 2:10 pm.

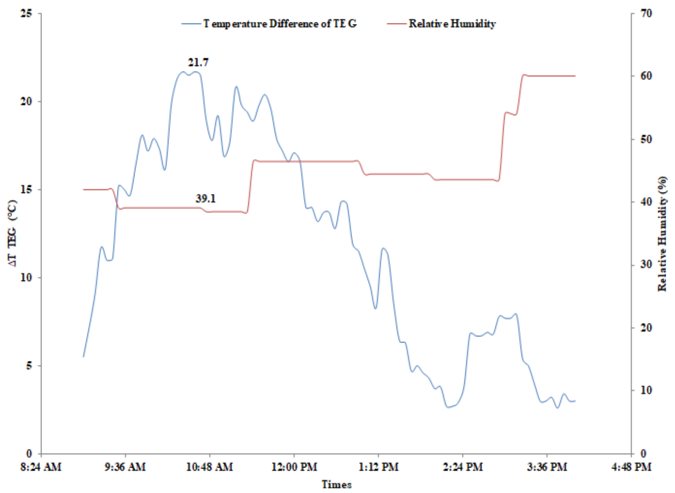


Fig. 6. Effect of Air Humidity on Temperature Difference in PV-Hybridized TEG

4.2 IoT and PV-TEG Performance

A comparison of the performance of 50 Wp polycrystalline and monocrystalline solar panels combined with TEG modules is shown in Figure 7. Although the hybrid performance of polycrystalline panels with TEG registers slightly higher values (6.53 to 6.56%) compared to monocrystalline panels (6.33 to 6.49%) within the period of 10:20 to 10:25 am, the overall efficiency of the monocrystalline PV integrated with TEG tends to be better. These results align with previous studies, though earlier findings reported a more significant difference in PV performance, exceeding 8% (Islam, 2024)(Vincent, 2021)(Ayadi et al., 2022)(A. S. Irshad, 2023). From Fig. 7 it can also be seen that the efficiency of monocystalline PV above 1pm is much higher than that of polycrystalline. This is because the type of polycrystalline PV material is not very resistant to high solar radiation intensity compared to monocystalline (Vincent, 2021). One potential reason for this discrepancy is using a 1kΩ resistor in the INA219 sensor module, which restricts the PV output current. This limitation also appears in the sensor used by (Rouhillah *et al.*, 2022), where the error rate reached 22%. Ideally, the error rate should be around 1% (Tamam & Aditia, 2023) or lower (B. Khudhair *et al.*, 2023) (Setiawan, 2023) (Wiyadi *et al.*, 2020).

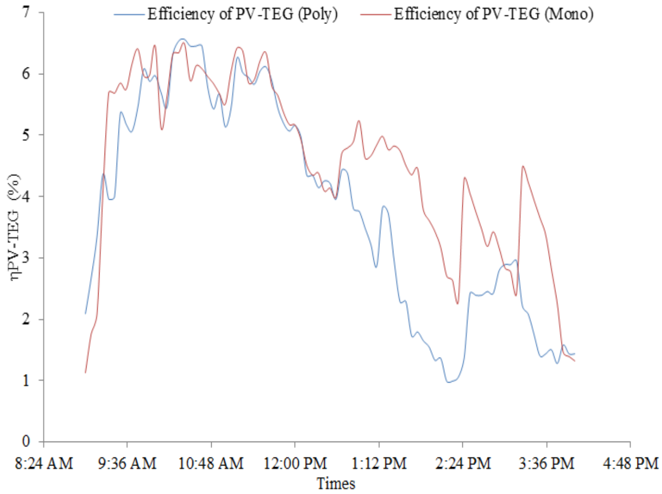


Fig. 7. The efficiency of hybrid PV-TEG; (a) PV Polycrystalline, (b) PV Monocrystalline

5. Conclusion

From the description above, it can be concluded that Monitoring the PV-TEG hybrid system using IoT has functioned optimally, displaying real-time sensor data on temperature, current voltage, relative humidity, and solar intensity. Although the electric current generated in the PV load is not as strong as that in the TEG circuit module, the sensor sensitivity—transmitting data to the Arduino IDE microcontroller and subsequently to the IoT system displayed on ThingSpeak.com—generally performs very well. This research also concludes that IoT monitoring effectively detects critical parameters affecting the PV-TEG combination's performance, particularly the temperature differences ranging from 2.7 to 21.7°C on both sides of the TEG modules. For further research, it is recommended to use more than one sensor for each parameter so that there is a comparison.

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