THERMOELECTRIC RECOVERY OF EXCESS HEAT IN PHOTOVOLTAIC MODULES AND AI-ASSISTED MONITORING

Tursunova Mohichehra Usmon qizi
Master,Uzbekistan
E-mail: [tursunovamohichehra1996@gmail.com]

Abstract

This paper examines the recovery of heat generated during the operation of a photovoltaic (PV) module using a thermoelectric generator (TEG) and the monitoring of temperature and electrical parameters based on AIoT. A comparative analysis of existing research articles is presented, highlighting the dependence of TEG output on temperature difference, thermal contact, and cooling methods. The proposed monitoring architecture is not the result of a new experiment but has been developed as a methodological framework for testing a future prototype.

Keywords: photovoltaic module, TEG, waste heat, temperature gradient, AIoT, energy harvesting, DC–DC converter.

INTRODUCTION

PV module efficiency depends on solar irradiance, ambient temperature, wind, electrical load, and the condition of the module surface. In their assessment of the energy and exergy efficiency of a 200 W panel, Basem et al. considered irradiance, wind speed, and ambient temperature, comparing an EANN model with a numerical model [1]. This approach highlights the importance of evaluating the panel's state using multiple variables rather than just a single parameter.

When a TEG is mounted on the back of a PV panel, it can convert a portion of the heat flux into electrical energy. In an experiment conducted by Demir, the energy generated by the TEG was utilized to power small monitoring devices; a maximum temperature gradient of 21.08°C and a maximum accumulated power of 458.64 mW were reported [2]. Another PV-TEG experiment yielded various voltage and current values under different water-cooling regimes [3]. These examples demonstrate the importance of heat dissipation on the cold side and the quality of the TEG contact.

II. METHODS

The analysis focused on four key questions: (1) how the panel's excess heat is collected; (2) how heat is dissipated from the TEG's cold side; (3) how the generated low-level power is conditioned and stored; (4) the basis of measurements upon which monitoring is linked to the control system. The results from the studies by Demir [2], Mitul et al. [3], Ramadhan et al. [4], and Garip et al. [5] were interpreted within the context of the relevant configurations.

In the proposed prototype, at least two temperature sensors are installed on the hot and cold sides of the TEG, while an additional sensor is placed on the rear surface of the PV module. PV voltage and current, TEG voltage and current, solar irradiance, and ambient temperature are recorded simultaneously. TEG power is determined using the formula PTEG = VTEG × ITEG. Power output after the converter and the energy entering the battery are also measured, as the TEG output differs from the energy actually available for use.

In the initial stage of AIoT monitoring, threshold checks and simple rule-based controls can be employed. Subsequently, once sufficient data has been collected, the forecasting of panel power and temperature using regression or neural networks will be tested. Model evaluation must include metrics such as prediction errors (MAE/RMSE), sensor failure detection accuracy, and data loss rates.

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III. RESULTS AND ANALYSIS

A review of the literature indicates that the benefits of a TEG are not limited solely to the generation of additional electrical energy; it can also influence the process of heat extraction from the panel. At the same time, the TEG itself introduces thermal resistance; if the cold side does not cool sufficiently, the temperature gradient decreases, resulting in reduced electrical output. Garip et al. note that TEG efficiency can be low due to a small temperature difference [5]. Therefore, the thermal contact material, heat spreader geometry, and airflow must be treated as distinct variables in the experimental design.

IV. DISCUSSION

When testing the system under Uzbekistan's hot and dusty conditions, factors such as high daytime temperatures, intense solar radiation, wind, and dust accumulation must be considered simultaneously. A single day of testing is insufficient to draw seasonal conclusions. To assess the reduction in panel temperature, it is necessary to compare the system with a control panel that lacks the TEG installation. The orientation, tilt, load, and cleanliness of both panels should be kept as consistent as possible.

The energy harvesting circuit may include a DC–DC converter, a battery, and a power management unit [2]. However, the converter's startup threshold and operational losses reduce the already limited power output of the small TEG. Consequently, recording only the open-circuit voltage is insufficient; current under load, power output, and stored energy must also be measured. Since the sensors themselves consume power, the energy autonomy of the monitoring system requires a separate energy balance analysis.

To prevent the AI model from overfitting to a specific day or panel, the data is divided into training, validation, and testing sets based on time. Sudden fluctuations in temperature and radiation, sensor errors, and data gaps affect the model's reliability. Critically important engineering decisions—such as overheating alerts, battery protection, and safe shutdown—must not rely solely on AI predictions but must be backed by independent threshold-based safety mechanisms.

4.1. Design requirements for a TEG-based system

Before mounting the TEG to the back of the panel, the thermal chain resistance must be evaluated: panel – thermal interface layer – TEG hot side – TEG cold side – heat spreader. Air gaps or uneven pressure at any interface can reduce heat transfer. Therefore, mounting pressure, the thermal interface material (paste or pad), cold-side heatsink geometry, and airflow conditions must be documented in the prototype specifications. Without controlling these factors, simply increasing the number of TEG modules does not guarantee higher electrical output.

The energy harvesting circuit must measure voltage and current under load, in addition to open-circuit voltage. The DC-DC converter's input voltage range and minimum startup threshold must match the TEG's variable output. Stored battery energy is calculated by integrating power over time; converter losses and the controller's standby power consumption must also be taken into account. In the work by Demir [2], a converter and a lithium-ion battery served to adapt energy for practical use; however, the results do not guarantee applicability to other electronics.

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Test parameter	Measurement method	Why it is necessary
Temperature difference	Calibrated sensors on the hot and cold sides of the TEG	Determining TEG operating conditions
TEG electrical output	Simultaneous measurement of V and I; $P = V \times I$	Avoiding incorrect conclusions based solely on voltage
PV electrical energy	PV voltage and current recorded over time	Assessing the impact of TEG installation on PV output
Auxiliary consumption	Power consumption of the converter, controller, communication, and cooling systems	Calculating the net energy gain
Comparison	Control module without the TEG installed	Distinguishing weather effects from TEG effects

4.2. Rules for interpreting results

In the experimental results report, it is insufficient to present the TEG's maximum voltage or current as a standalone metric. Electrical power must be derived from simultaneously measured voltage (V) and current (I) values, while energy over time should be calculated as the integral of power. If only short-term peak values are recorded, they cannot be interpreted as representing stable generation over an entire day or season. Furthermore, a drop in panel temperature does not automatically imply an increase in total system energy; the TEG's thermal resistance and the power consumption of auxiliary electronics also factor into the overall energy balance.

When evaluating the AI model, measurements must be partitioned into training, validation, and test sets based on time. Randomly splitting sequential measurements from the same day can artificially inflate the model's apparent accuracy. An initial rule-based model is retained as a baseline benchmark. The model's utility is assessed not only by error metrics but also by the impact of false alerts and its influence on energy management decisions.

4.3. Measurement uncertainty and control conditions

If a temperature sensor is installed on the hot or cold side of the TEG without adequate thermal contact, the measured temperature may differ from the actual module surface temperature. Therefore, the sensor location, mounting method, and calibration data are included in the protocol. When measuring the electrical parameters of the PV module and TEG, the internal resistance of the voltmeter or ammeter and the connection circuit may affect the results. For TEG power output, voltage and current must be measured simultaneously, and the measurement interval must be sufficient to capture temperature fluctuations.

In the absence of a reference panel, it is difficult to attribute a drop in panel temperature or a change in electrical output solely to the TEG installation. Since solar irradiance and wind conditions can change rapidly, the test and reference modules are positioned close to each other, sharing the same orientation and tilt. If the nominal specifications of the two panels differ, their initial I–V characteristics or baseline power outputs under identical conditions are recorded. During data analysis, the differences between measurements and potential uncertainties are explicitly stated.

4.4. Minimum data for reporting results

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When reporting test data in a scientific article, the following information must be provided at a minimum: technical specifications of the panel and TEG; electrical connection diagram; measurement instruments and their accuracy; test timing and weather conditions; and the number of repetitions. raw data processing method; all auxiliary costs; comparison with a control module. Instead of presenting only peak values, it is recommended to provide data alongside time-series or dispersion metrics. This thesis does not claim that these data represent final measurements; rather, it designates them as requirements for future prototype testing.

V. CONCLUSION

Integrating heat harvesting from PV modules via TEGs with AIoT monitoring represents a promising approach for autonomous sensors and power monitoring. Existing experiments demonstrate the importance of temperature gradients, heat dissipation, and energy matching, though results depend on the specific configuration. The next stage requires parallel testing with a control panel, an analysis of the net energy balance, and the collection of seasonal data.

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