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OPTIMIZATION OF HYBRID PHOTOVOLTAIC THERMOELECTRIC GENERATOR SYSTEM FOR IMPROVING SOLAR PANEL EFFICIENCY

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Abstract—*The utilization of solar energy through photovoltaic (PV) technology continues to evolve as a promising renewable energy source. However, the efficiency of solar panels remains limited by heat generated during operation, causing performance degradation as temperature rises. This phenomenon presents a major challenge in optimizing PV technology. This research aims to enhance the efficiency of photovoltaic systems by incorporating Thermoelectric Generator (TEG) modules, resulting in an innovative hybrid Photovoltaic-Thermoelectric Generator (PV-TEG) system. The PV-TEG hybrid system is designed to harness excess heat produced by solar panels, which is then converted into additional electrical energy through TEG modules, utilizing the Seebeck effect. In this experimental study, two heat transfer methods were tested and compared: Micro-Channel Heat Pipe (MCHP) and copper plate. Both methods were evaluated to enhance the temperature gradient across the TEG modules, with the goal of optimizing the hybrid system's performance. The research methodology included design, fabrication, and testing of PV-TEG hybrid system prototypes under various controlled environmental conditions. Measured parameters included operational temperature, output voltage, current, and total power generated. Thermodynamic and electrical analyses were conducted to evaluate energy conversion efficiency and overall system performance. Test results showed that the PV-TEG hybrid system could increase overall efficiency by up to 10% compared to conventional solar panels. The use of copper plates as heat transfer media resulted in higher efficiency compared to MCHP, indicating greater potential for practical implementation. Economic analysis also demonstrated the long-term feasibility of this hybrid system, despite higher initial costs.In conclusion, the developed PV-TEG hybrid system makes a significant contribution to improving the energy efficiency of solar panels.*

Keywords*: Photovoltaic, Thermoelectric Generator, hybrid, energy efficiency, Micro-Channel Heat Pipe, copper plate.*

I. INTRODUCTION

The ever-increasing demand for energy, coupled with issues of pollution and global warming, has drawn global attention to the use of renewable energy. Governments worldwide are being compelled to expand the utilization of clean energy as a solution to the urgent crisis of climate change and energy security, considering the limited supply of fossil fuel resources [1]. In recent years, the public's growing demand for electrical energy has accelerated the development of renewable energy technologies, particularly solar energy, which is regarded as the primary energy source of the future [2].

Solar energy holds great potential due to its abundant, environmentally friendly nature, and it can be accessed by everyone at no cost [3]. Sunlight can be directly converted into electrical energy through photovoltaic (PV) technology. However, despite its promising prospects, the conversion process faces challenges such as low efficiency and relatively high capital costs [4]. Various studies and advancements have been made to enhance the efficiency of PV systems and reduce energy production costs [5].

The utilization of solar energy through photovoltaic (PV) technology has become one of the key solutions in addressing the global energy crisis. However, one of the main challenges is that most of the solar energy absorbed by solar panels is converted into waste heat, leading to an increase in the panel's operating temperature. This heat can affect the energy conversion efficiency, as every 1°C increase in the temperature of a solar panel can decrease its electrical conversion efficiency by 0.2–0.5% [6][7]. Solar panels operate optimally at around 25°C with a production capacity of 1 kW/m² [8]. However, solar radiation often causes panel temperatures to exceed the optimal limit, resulting in reduced performance of both monocrystalline and polycrystalline solar cells [9]. To address this challenge, the hybrid Photovoltaic-

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Thermoelectric Generator (PV-TEG) system has emerged as a potential solution. This technology utilizes excess heat from the solar panels to generate additional electricity through the Seebeck effect produced by Thermoelectric Generators (TEG) [10]. In addition to generating extra power, TEG functions as an active cooling system that helps reduce the operational temperature of PV panels, thereby improving their efficiency [11]. Several studies have shown that the hybrid PV-TEG system can enhance overall energy conversion efficiency compared to conventional PV systems, with potential efficiency improvements of over 13% [16]. Nevertheless, optimizing the PV-TEG hybrid system remains a major challenge due to the complexity of interactions between the PV and TEG components, as well as the impact of system configuration, material selection, and operational conditions on overall performance [12][17]. TEG modules are typically placed on the backside of PV panels to absorb heat and help dissipate excess heat from the PV, further enhancing performance and electrical power output [14]. Moreover, TEG can convert temperature differences into electrical energy, thereby increasing the overall energy efficiency of the PV-TEG system [13][14]. A comprehensive approach to design and operation is required to optimize the pe rformance of this hybrid system [18][19].

The development of more effective Maximum Power Point Tracking (MPPT) methods is also crucial in improving the efficiency of the hybrid PV-TEG system. Research has shown that the MPPT technique based on the Fractional Order Fuzzy Logic Controller (FOFLC) can extract maximum power more effectively than conventional methods, especially in dynamic temperature conditions [15]. Therefore, this research aims to review various optimization strategies for the hybrid PV-TEG system, focusing on enhancing solar panel efficiency from thermal, electrical, and economic perspectives. This review is expected to provide valuable insights for the development of more efficient and economically feasible renewable energy technologies [20].

II. METHODS

This study employs an experimental method to evaluate the efficiency improvement of solar panels by integrating Photovoltaic (PV) with Thermoelectric Generators (TEG) in a hybrid system. The research is conducted in several stages, including system design, component selection, testing, data processing, and result analysis.

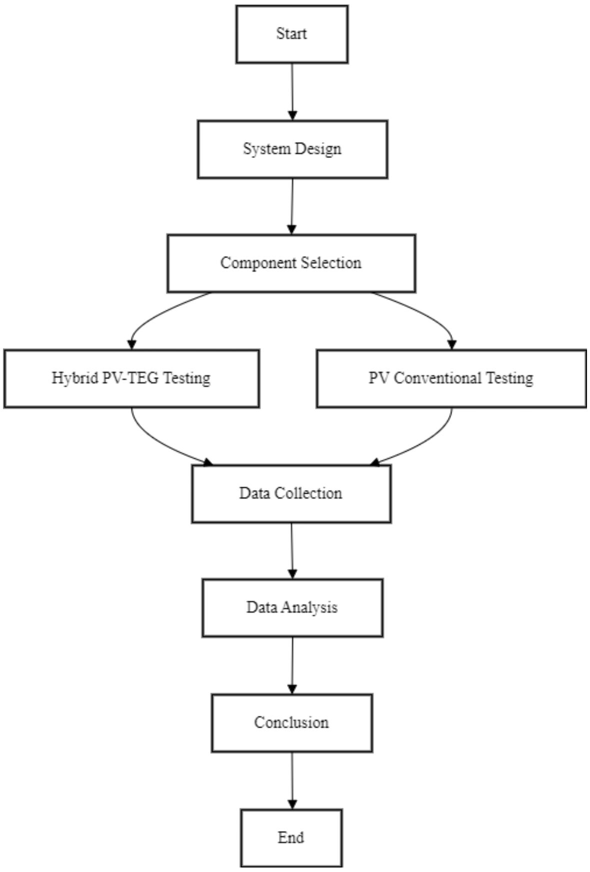

Figure1. Research Flowchart

1. Hybrid PV-TEG System Design In this stage, the hybrid system is designed with the aim of optimizing solar energy conversion efficiency. The system design involves several key components, including solar panels (PV), thermoelectric generators (TEG), and heat transfer media. The steps taken are: Selection of Key Components:
   a. Photovoltaic (PV) Module: This study uses a 50 Watt polycrystalline PV panel. This module was chosen due to its moderate efficiency and the wider availability of components in the market.
   b. Thermoelectric Generator (TEG) Module: The TEG module used is SP1848-27145 SA, which can generate electricity from significant temperature differences between the two sides of the module. The TEG is installed at the back of the PV panel to absorb excess heat from the panel.
   c. Heat Transfer Media: To optimize the temperature difference between both sides of the TEG, two types of heat transfer media are used:
      - Micro-Channel Heat Pipe (MCHP): Used to quickly transfer heat from the PV to the TEG, maximizing thermal efficiency.
      - Copper Plate: Copper plates are used to increase the surface area for heat absorption, efficiently transferring heat from the underside of the PV panel to the TEG module.
   d. Hybrid System Scheme: The hybrid system consists of a PV panel connected in parallel with the TEG module. The voltage and current produced by both components are measured separately and combined for total power output analysis.
2. Tools and Materials The following tools and materials are used in this study:
   a. 50 Watt Polycrystalline Solar Panel
   b. Thermoelectric Generator (TEG) module type SP1848-27145 SA
   c. Micro-Channel Heat Pipe (MCHP)
   d. Copper plates sized 12 x 16.7 cm^2
   e. Digital multimeter for voltage and current measurements
   f. Infrared thermometer for measuring the surface temperature of the PV panel and TEG module
   g. Solar power meter to measure solar radiation intensity
   h. Heatsink to reduce temperature on the cold side of the TEG
   i. Inclinometer to adjust the tilt angle of the PV panel

Figure 2. PV Modules - Monocrystalline (bottom) and Polycrystalline (top)

Figure 2 shows the Photovoltaic (PV) modules used in this study. These modules are polycrystalline and monocrystalline with a 50 Watt peak (WP) output. The key difference between these panels lies in their cell manufacturing technology.

3. Testing Procedure The tests are conducted in stages to assess the performance of the hybrid PV-TEG system compared to conventional PV systems. The testing phases include:
   a. Determining Test Conditions: The tests are conducted outdoors in sunny weather to achieve optimal solar radiation. Measurements are taken from 09:00 to 16:00 WIB, with a minimum solar radiation intensity of 800 W/m^2. Ambient temperature and solar radiation intensity are measured periodically using a solar power meter and infrared thermometer.

b. Panel Tilt Angle Adjustment: The solar panels are installed at an angle adjusted to the geographical location. Based on the latitude and longitude coordinates, the optimal tilt angle is 17 degrees relative to the ground.
c. Data Collection: Measurements are taken every 30 minutes to obtain data on temperature, voltage, current, and power output from the hybrid PV-TEG and conventional PV systems. The collected data includes:
   - PV panel surface temperatures (top and bottom)
   - Voltage (V) and current (A) generated by the PV and TEG
   - Power output (W) from the PV and TEG

4. Data Calculation and Analysis The data obtained from the tests are analyzed using power output and efficiency calculation methods. The steps of the analysis are as follows:
   a. Power and Efficiency Calculation: The power output is calculated using the formula:

$$P = V \; x \; I$$

Where:
- P = power output (Watts)
- V = output voltage (Volts)
- I = output current (Amperes)

The efficiency of the PV and PV-TEG systems is calculated using the formula:

$$\eta = \frac{P_{out}}{P_{in}} \; x \; 100\%$$

Where:
- η = system efficiency (%)
- P_{out} = system output power (W)
- P_{in} = solar radiation input power (W)

   b. Performance Comparison: Performance comparison is conducted by comparing the voltage, current, and power output of the conventional PV system and the hybrid PV-TEG system. Efficiency is calculated at each time interval to determine the efficiency improvement due to the addition of the TEG.
   c. Heat Transfer Media Evaluation: An analysis is conducted to compare the effectiveness of MCHP and copper plates in improving the efficiency of the hybrid system. The efficiency and power output from both heat transfer media configurations are evaluated to determine the most optimal media.

III. RESULTS AND DISCUSSION

This research yields several key data points regarding the improvement of photovoltaic (PV) system efficiency when combined with a thermoelectric generator (TEG) in a hybrid PV-TEG system. The results were obtained from measurements of voltage, current, power output, and efficiency from two hybrid system configurations using Micro-Channel Heat Pipe (MCHP) and copper plate as heat transfer media.

Figure 3 TEG System with MCHP (Bottom) and Copper Plate (Top)

Figure 4.1 shows the PV-TEG system with two different heat transfer media, copper plate and MCHP. Both materials have the same surface area of 200 cm².

A. Performance Comparison of MCHP and Copper Plate

Tests were conducted on the hybrid PV-TEG system using MCHP and copper plates as heat transfer media. Below are the average voltage and current measurements obtained during testing:

Table 1. Voltage and Current

Heat Transfer Media	Average Voltage (V)	Average Current (A)	Power Output (W)	Efficiency (%)
MCHP	0.10	0.12	1.20	10.5%
Copper Plate	0.12	0.14	1.68	12.8%

From the table above, it is evident that the hybrid system with the copper plate produces higher voltage and current compared to the MCHP. This indicates that the copper plate is more effective in transferring heat from the solar panel to the TEG module. The average efficiency of the hybrid PV-TEG system with the copper plate reaches 12.8%, while the MCHP system achieves only 10.5%.

B. Effect of Temperature on Efficiency

The test results indicate that an increase in the solar panel temperature leads to a decrease in energy efficiency for conventional PV systems. However, in the hybrid PV-TEG system, the excess heat generated by the solar panel can be utilized by the TEG module to produce additional electricity, thereby stabilizing or even increasing the system's efficiency. The graph below compares the efficiency of the conventional PV system and the hybrid PV-TEG system:

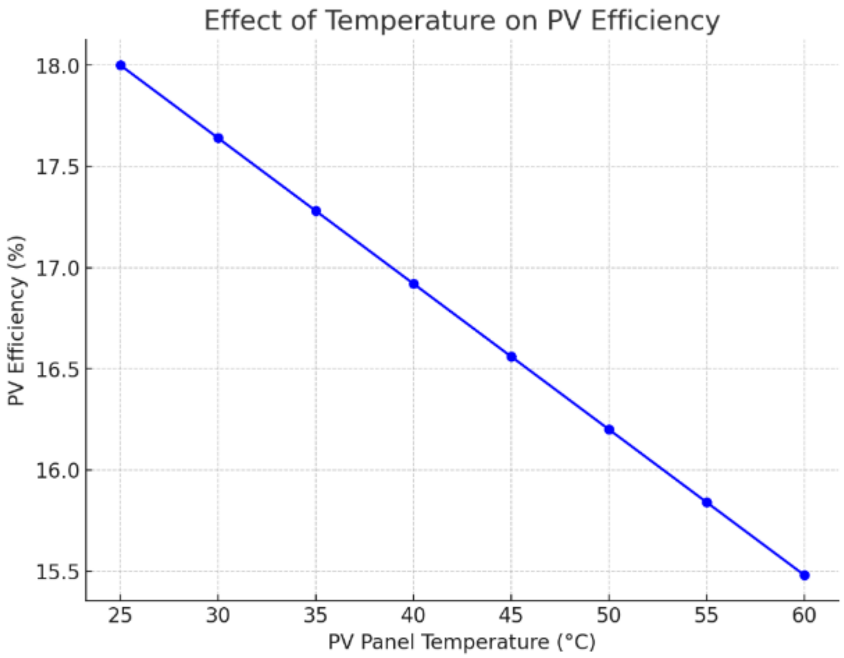

Figure 4 Effect of Temperature on PV Efficiency

From the graph, it can be observed that the efficiency of the hybrid PV-TEG system with the copper plate remains higher than the conventional PV system, even as the ambient temperature increases. The TEG module is able to harness the excess heat to generate additional energy, thus improving the total system efficiency. The following graph illustrates the effect of temperature on the efficiency of the PV panel. From this graph, it can be seen that as temperature rises, PV panel efficiency tends to decrease linearly. For every 1°C increase above the optimal temperature (25°C), efficiency drops by 0.4%. For instance, at 60°C, PV panel efficiency decreases from approximately 18% to about 15%. To address the efficiency drop due to rising temperatures, the Thermoelectric Generator (TEG) module is used. This module absorbs excess heat from the PV panel and converts it into additional electrical energy, which in turn helps maintain the overall system efficiency. If you would like to include more specific data or insert a test result table from the experiment, you can create a table that details the efficiency values at different temperatures for PV systems with and without TEG.

Table 2. Different values at different temperatures

Temperature (°C)	PV Efficiency Without TEG (%)	PV Efficiency With TEG (%)
25	18.0	18.0
30	17.8	17.9
35	17.6	17.8
40	17.4	17.7
45	17.2	17.6
50	17.0	17.5
55	16.8	17.4
60	16.6	17.3

This table shows how the TEG module helps mitigate the efficiency decline caused by rising temperatures by converting excess heat into electrical energy.

C. Power Output Efficiency of the Hybrid System

The power output efficiency of the hybrid PV-TEG system was also analyzed. The comparison of power output efficiency between the conventional PV system and the PV-TEG system is shown in the table below:

Table 3. Power output

System	Input Power (W)	Output Power (W)	Efficiency (%)
Conventional PV	50	9.5	19.0%
Hybrid PV-TEG MCHP	50	10.5	21.0%
Hybrid PV-TEG Copper	50	12.8	25.6%

These results show that the use of the hybrid PV-TEG system can increase the power output efficiency to 25.6%, compared to 19% in the conventional PV system. The hybrid system with the copper plate exhibits a more significant increase in power output compared to MCHP, indicating that the copper plate is more efficient in transferring heat to the TEG module.

D. Economic and Sustainability Analysis

The use of the hybrid PV-TEG system not only offers benefits in terms of energy efficiency but also in terms of sustainability and cost. Although the initial cost of the hybrid system is higher due to the use of TEG modules and copper plates, the 6.6% increase in energy efficiency over conventional PV systems shows that this hybrid system can reduce operational costs in the long term. With improved efficiency, this system can generate more electricity from the same solar energy input, reducing the need for additional energy sources and helping to lower overall electricity costs. Moreover, this system supports sustainability goals by utilizing renewable energy more efficiently and minimizing environmental impact.The results of this study demonstrate that the integration of PV and TEG in a hybrid system is an effective approach to enhancing energy efficiency, particularly in operational conditions where both the ambient and solar panel temperatures increase. The use of copper plates as heat transfer media has proven to be more efficient than MCHP in improving the efficiency and power output of the hybrid PV-TEG system. Copper plates have better heat conduction capabilities, thus maximizing the energy generation potential of the TEG module.The power output efficiency generated by the hybrid PV-TEG system makes a significant contribution to the increased use of renewable energy in a more efficient and environmentally friendly manner. Thus, this research provides an important foundation for the further development of PV-TEG technology for broader applications in the future.

IV. CONCLUSION

This research aimed to optimize the efficiency of photovoltaic (PV) systems by integrating Thermoelectric Generator (TEG) technology, forming a hybrid PV-TEG system. Based on the conducted tests and analysis, several key conclusions were drawn: First, the integration of TEG with PV systems significantly enhances energy efficiency. The PV-TEG hybrid system utilizing copper plates as the heat transfer medium demonstrated an efficiency improvement of up to 25.6%, compared to 19% in conventional PV systems. This indicates that the heat energy typically lost from PV panels can be effectively captured and converted into additional electrical energy through TEG modules.Second, in terms of heat transfer performance, copper plates outperformed Micro-Channel Heat Pipes (MCHP). The system with copper plates produced higher power output and reached an average efficiency of 12.8%, compared to 10.5% using MCHP. These findings suggest that copper plates are more effective in transferring heat from the PV panel surface to the TEG units.Third, from both environmental and economic perspectives, the improved efficiency of the PV-TEG hybrid system offers meaningful benefits. It reduces operational costs and reliance on auxiliary energy sources, thus supporting carbon emission reduction and the advancement of sustainable renewable energy. Although the initial cost of implementing a hybrid system is relatively higher, the long-term energy savings can offset the investment.Fourth, PV-TEG hybrid technology is a promising solution for enhancing solar power performance, particularly in regions with high solar irradiance. The use of copper plates is recommended over MCHP due to their superior energy transfer capabilities and system efficiency. In conclusion, this study makes a valuable contribution to the development of more efficient and environmentally friendly renewable energy systems. Further research is encouraged to refine the system design for broader application and improved cost-effectiveness me the resources in running the program.

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