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Increasing energy and exergy efficiency in photovoltaic panels by reducing the surface temperature with thermoelectric generators

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ABSTRACT

Many factors affect the efficiency of photovoltaic panels (PV), which convert solar energy directly into electrical energy. Among these factors, temperature is one of the most important one. While some of the radiation from the sun is converted into electrical energy, part of it emerges as heat energy. This causes the photovoltaic cells to heat up and reduce their electrical efficiency. Different methods are used in the literature to reduce the temperature in PV panels. In this study, in order to reduce the adverse effects caused by the high temperature in the PV panels, 30 Thermoelectric Generators (TEG) were applied to the back surface of the PV panel to increase the PV panel output power and to produce additional electrical energy. Energy and exergy analysis made on the data obtained from both PV panels in the climatic conditions of the installation site showed that the temperature of the PV panel is reduced, and the energy and exergy efficiency is increased with the TEG application. At the end of July, August, and September, when the experiments were carried out, an average of 8.4% more electrical energy was obtained from a single PV panel with TEG, compared to the standard PV panel. Our results suggests that combination of TEG with PV panels could significantly increase the electrical energy, especially when a series of PV panels are used together.

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Photovoltaic; temperature; power; energy; exergy

Introduction

Recently, investments in electricity generation from renewable energy sources, especially solar and wind energy, have been increasing. However, when the performance of photovoltaic cells in the natural field environment is compared with the version of the standard test conditions, the efficiency of the PV panels decreases with the increase in temperature due to radiation (Bel Hadj Brahim Kechiche, Hamza, and Sammouda 2016). Since the energy that cannot be converted into electricity increases the photovoltaic surface temperature, it causes damage to the PV panel module cells and leads to reduced service life of the PV panels (Enescu and Spertino 2017). When the studies in the literature about reducing the heat losses in photovoltaic panels (PV) are examined; A water-cooled nozzle spray system has been developed that significantly reduces the module cell temperature (Benato and Stoppato 2019). The factors affecting the performance of PV panels and the applications that can be made to increase the panel power are explained in detail (Fouad, Shihata, and Morgan 2017).To obtain higher efficiency by cooling the PV panel surface, the panel output power and the cell's lifetime are increased with different cooling methods (Siecker, Kusakana, and Numbi 2017). To prevent the decrease in PV panel power output with temperature increase, new models are proposed on the bottom surface. In experiments carried out under natural conditions, it has been determined that the panel temperature can be reduced by 10°C with the evaporative cooling model and the power improvement is 5% (Haidar, Orfi, and Kaneesamkand 2021). The electrical conversion efficiency of

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PV panels, which are widely used in today's applications, is around 20%. If the temperature increase in the PV panels cannot be prevented, the efficiency decreases even more (Aly, Ahzi, and Barth 2019; Kalkan et al. 2019). Many parameters can affect the energy, exergy and conversion efficiency in the design and analysis of solar energy systems. The density of solar radiation directly affects the heating of photovoltaic cells (Coskun, Oktay, and Dincer 2011). For this reason, to reduce the losses caused by the heat, a DC fan with low electrical energy consumption is proposed to create airflow on the back surface of the PV panel and to remove the hot air by convection (Joshi et al. 2009). İnvestigated different methods for cooling the PV panels, taking into account the advantages of each method in cooling down the panel surfaces in an effective way (Nizetic, Giama, and Papadopoulos 2018). With the particular convective cooling profiler used behind the PV panels, the module cell temperature has been reduced, resulting in an efficiency increase between 2.5% and 4.5% in the PV panel power output (Nizetic et al. 2016). The most effective method in PV panel performance has been achieved with water-based cooling techniques, and an average of 10% to 20% performance increase has been completed. However, it should be noticed that active-based water cooling is not economical and not easy for optimization. A different passive cooling method has been applied to prevent the temperature increase in PV panels. With the PCM application, a performance increase between 2.5% and 10.7% have been achieved in the PV panel power output (Nizetic et al. 2021; Nizetic, Papadopoulos, and Giama 2017). In a different study, water was used to cool the other side of the thermoelectric generator, which extracts heat from the PV panel surface. By keeping the PV panel surface temperature at a constant temperature, the efficiency increases between 4% and 20% seasonally (Metwally et al. 2021). Another PV panel cooling method aims to increase power generation by using phase change material and thermoelectric generator systems together. The heat energy generated in the PV panel is increased by reducing the PV panel surface temperature with thermoelectric generators and numerical simulations. Depending on the simulation results, it was observed that the PV panel efficiency improved by 1.66% (Naderi, Ziapour, and Gendeshmin 2021). In a different study, a decrease of 3°C in photovoltaic surface temperature with aluminum material and 7.35°C with copper material were achieved by applying a passive heatsink to the lower surface of the panels (Parkunam et al. 2020).

In a study using phase change materials (PCM) to reduce the operating temperature of the PV panel, higher performance was obtained compared to a conventional PV module, especially during the hottest months. (Aneli, Arena, and Gagliano 2021) showed that 3.5–10% more electrical energy could be obtained from a PV panel using PCM all year long. To reduce the temperature in the PV modules and increase efficiency, the cooling of PV panels with water and air was compared in an experimental setup established in Italy Calabria University, Department of Mechanical Engineering. With the spray water method, 2.78 m^3 of water was used throughout the season, resulting in an increase of up to 8.6% per month in the PV panel output power (Bevilacqua et al. 2020). An effective thermal management system (TMS) helps to improve the efficiency of PV panels by dissipating the generated heat and therefore, the output power will be increased. Due to the capability of PV cells to convert a specific wavelength to the irradiation energy, the rest is turned into waste heat, which, in turn, decreases the efficiency. Similar to other applications of thermal management such as Li-ion battery packs, there can be active or passive cooling systems. Liquid and air cooling systems are more conventional and practical, while recent methods such as heat pipes, phase change materials and Thermoelectric devices are also considered for TMS purposes. The latter one is the main focus of the current study. In a passive cooling system of PV panels, the heat removal process is based on radiation and free convection. Once these two mechanisms are not effective in specific operating conditions, there will be limitations in cooling down the cells and thereafter, the efficiency will decrease (Royne, Dey, and Mills 2005). For active or passive cooling systems, the heat transfer fluid (HTF) can be considered to be air or water. Lack of water in for cooling the PVs, makes the air as an alternative, but studies show that the air has not enough cooling power (Xu et al. 2012), although there are methods such as adding nanoparticles to increase the volumetric heat absorption and making the heat transfer more effective (Bonab and Javani 2019). Therefore, forced convection increases the heat transfer in an air-cooled system in an active cooling system. Liquid cooling in different configurations can be used for cooling

PV cells as another active cooling system (Rosa-Clot, Rosa-Clot, and Tina 2011). have considered a rather feasible configuration where a thin layer of water flows over the PV cells in a confined passage to absorb the dissipated heat from the infrared incident light. 2.5 cm thick serpentine channels were considered in their configuration to attain a light structure. On the back surface, there was also an absorbing plate for thermal collection purposes. Their eight-month experimental data collection showed the effectiveness of the considered cooling system and increased the photovoltaic cells' efficiency. Other systems with hybrid cooling methods and refrigerants are considered in a study by (Makki, Omer, and Sabir 2015) in which they have shown that thermoelectric cooling systems can play a noticeable role in increasing the efficiency of photovoltaic cells by creating a cooling effect. Thermoelectric cooling systems (TEC) can be integrated with PV/T systems for cooling applications. (He et al. 2013) simulated the application of thermoelectric generating mode (TEG) theoretically and showed that thermoelectric modules enhance the cooling capacity and thereafter the electrical efficiency of the system. In another attempt, the same authors (He et al. 2014) have presented the experimental results of employing thermoelectric modules in winter and energy, exergy analyses have been done for summer and winter modes and the results were verified by an established small-scale system.

To prevent PV cell degradation and increase its efficiency Najafi and Woodbury (2013) have studied a PV cell with a thermoelectric module attached to its backside. Using a mathematical model developed in MATLAB, they have used PV generated power to run the thermoelectric cooling mode. They have applied an optimization approach based on the genetic algorithm to determine the optimum power required for the thermoelectric modules by minimizing their power consumption and therefore improving the overall efficiency of the PV cell. Furthermore, the maximum temperature of the cell was kept limited. Their results show that lower temperatures can be obtained in photovoltaic cells by using thermoelectric cooling modules with reasonable electric energy consumption by the thermoelectric cooling devices at the back of the surface.

There are studies in the literature on cooling PV panels by utilizing the peltier effect of thermoelectric elements. However, when thermoelectric materials are used for cooling by supplying electrical energy, they consume a lot of electrical energy because the current drawn is high. For this reason, the cooling methods utilizing the peltier effect of thermoelectric elements in PV panel systems are not considered to be economical.

In this study, we aimed to reduce the PV panel temperature by utilizing the seebeck effect of the thermoelectric element and to generate additional electricity from waste heat. For this purpose, 30 thermoelectric generators (TEG) with cooling fins made of aluminum material were fixed under the PV panel. Unlike most of the studies on cooling of PV panels in the literature, where data recorded over a short period of time and the total amount of energy produced in PV panels is not examined, we designed a special automation system that allowed to measure and record the voltage, current and temperature of PV panels by means of a data acquisition circuit throughout the experimental period. By this setup we were able to monitor, record and compare the instantaneous power output between the standard PV panel and TEG panel and the total amount of electrical energy produced during the summer season.

The study were carried out in the real climatic conditions in June, July and September at the Trakya University campus in Edirne province, where there is no study examining the seasonal effect of temperature on performance of PV panels and the effect of reducing the PV surface temperature on gaining electrical energy from waste heat.

Methodology

The temperature increase in the photovoltaic cells used during the conversion of solar radiation into electrical energy reduces the efficiency of the PV panels. Therefore, it is aimed to reduce the temperature in the photovoltaic cells by taking advantage of the Seebeck effect of the Thermoelectric Generators (TEG) that we apply to the lower surface of the PV panel. Thanks to this method, the PV panel output power will increase, and some additional electrical energy will be produced from TEGs. However, the voltage and current values of the extra electricity produced are directly proportional to the temperature difference between the TEG surfaces. Various methods are used for cooling TEGs in applications. Since there is no moving part on the system that consumes energy and cost considerations, the cooling method with aluminum fins is preferred.

To reduce the temperature of the first PV panel on the system and generate additional electrical energy, 30 TEGs were applied to the lower surface at equal intervals. A group was formed by connecting 10 series of TEGs. Thus, 3 groups connected in series were obtained. Serial groups consisting of 10 TEGs were also joined in parallel, and the circuit that would generate additional electrical energy was completed. The second PV panel is in standard form to compare the amount of electrical energy produced. The third PV panel has the power to enable the system's electronic components to work. In addition, the third PV panel charges the battery for uninterrupted operation of the system on days when there is no solar radiation. Therefore, the output power of this PV panel is not measured. The setup circuit is shown in Figure 1.

As can be seen from thermoelectric effect Equations (1) and (2) obtained energy amount increases when Seebeck coefficient is kept constant and high-temperature difference is ensured. Seebeck coefficient is an important parameter for increasing conversion efficiency. Due to Wiedemann-Franz rule of isotropic metal, semiconductor are usually used as thermoelectric material (Uchida et al. 2016; Wang, Xiao, and Zhao 2021).

$$V = \alpha(T_h - T_c) \tag{1}$$

$$P = Q_h - Q_c = I^2 R\widetilde{\Delta}(T_h - T_c) \tag{2}$$

where; V is the voltage difference between two different metals or semiconductors; α is Seebeck coefficient; $T_h - T_c$ is temperature difference between hot and cold sides; R is electrical resistance; P is electrical power; I is electrical current.

The main objective is to maximize the current, which corresponds to the short circuit and zero resistance, as shown in the equation (Royne, Dey, and Mills 2005):

$$I = \frac{\alpha(T_h - T_c)}{R_L + R} \tag{3}$$

In such a condition, the modules maximum current would be:

$$I_{max} = \frac{\alpha(T_h - T_c)}{R} \tag{4}$$

The Seebeck effect is considered independent of temperature to make the heat diffusion equation more simplified. If the contact resistances and radiation, convection at the surfaces are negligible, then the heat equation can be written as:

$$\frac{d}{dx}\left[kA\frac{dT}{dx}\right] + \frac{I^2\rho}{A} = 0 \tag{5}$$

Variable operating temperature in photovoltaic affects the efficiency of the cell. Therefore, predicting the heat transfer mechanisms and the behavior of the temperature changes is important. In predicting the temperature changes, the only affecting mechanism is not convection. Radiation and conduction can also affect the operating temperature and heat flux in the photovoltaic cell (Tina and Gagliano 2016) introduced a multi-layer model (MLM) for a precise evaluation of photovoltaic cell temperature at the front and back of the cell. One interesting aspect of the study is considering radiation, convection, and conduction in calculating the thermal flux.

"Technically, there is no difference between the temperature changes in a conventional photovoltaic cell and a combined photovoltaic and thermal collector cell (PV/T) except for the heat sink due to the passing fluid absorbing the dissipated heat from the cell back surface. Hottel–Whillier equation is used to describe the thermal efficiency of the collector concerning the temperature" (Ventura et al. 2021).

$$\eta_{th} = F_R \cdot (\tau \cdot \alpha) - F_R \cdot U_L \left(\frac{T_{\min} - T_{amb}}{G} \right) \tag{6}$$

where F_R= collector heat removal factor; U_L= collector overal heat loss coefficient factor (W/m^2K); ($\tau \cdot \alpha$) = transmittance-absorptance product without electrical output T_{amb}= ambient air temperature (K); T_{min}= inlet temperature (K); G = irradiance (W/m^2).

PV efficiency

Energy efficiency

Energy analysis is conducted to determine energy input and output in a system. It gives numerical values about the amount of input energy used for the determined purpose and the amount of energy wasted. Examining this kind of analysis can give data about how the energy is used and how enhancements can be made. Energy analysis is based on the first law of thermodynamics. The ratio of energy output to the energy transferred to solar PV panels can be used to measure solar PV efficiency. Energy efficiency can be defined as the ratio of the input energy to the output energy. The present study used solar energy as energy input and electricity power obtained from PV panels as energy output. Input energy of solar radiation can be defined as follows (Bayrak et al., 2017).

$$\dot{E}_{solar} = I_s \cdot A \tag{7}$$

Here, I_s is the global solar radiation and A is the PV panel area. On the other hand, the output energy is the electric energy obtained from PV panel ($\dot{E}_{out} = \dot{E}_{elect}$). Energy efficiency can be defined as the ratio of the input energy (solar radiation) of the system to the output energy (real electric output) of the system (Gao and Meng 2020; Sahin, Dincer, and Rosen 2007).

$$\eta = \frac{\dot{E}_{out}}{\dot{E}_{in}} = \frac{\dot{E}_{elec}}{\dot{E}_{solar}} = \frac{FF \cdot V_{OC} \cdot I_{SC}}{I_S \cdot A} \tag{8}$$

where, FF is fill factor, V_{OC} is open-circuit voltage and I_{SC} is short circuit current.

Exergy efficiency

In order to understand the real energy potentials of systems, exergy analyses based on the second law of thermodynamic should be conducted as well as energy analysis. Exergy can be defined as the theoretically obtainable maximum work potential. Energy analysis conducted according to the first law of thermodynamics is not sufficient to reveal the maximum energy amount. Therefore, in order to demonstrate the maximum usable energy in any system, exergy analysis must be conducted based on the second law of thermodynamics. Exergy analysis enables enhancements in systems since they help to observe the efficiency of systems according to energy and how much work can be obtained from systems. The exergy output of PV panel can be calculated as follows (Sudhakar and Srivastava 2014):

$$\dot{E}x_{out} = \dot{E}x_{elec} \tag{9}$$

where $\dot{E}x_{elec}$ is the electrical exergy, which is equal to the electric power generated by the solar PV panel and thermoelectric generator (Shittu et al. 2020):

$$\dot{E}x_{elec} = V_{OC} \cdot I_{SC} + P_{TEG} \tag{10}$$

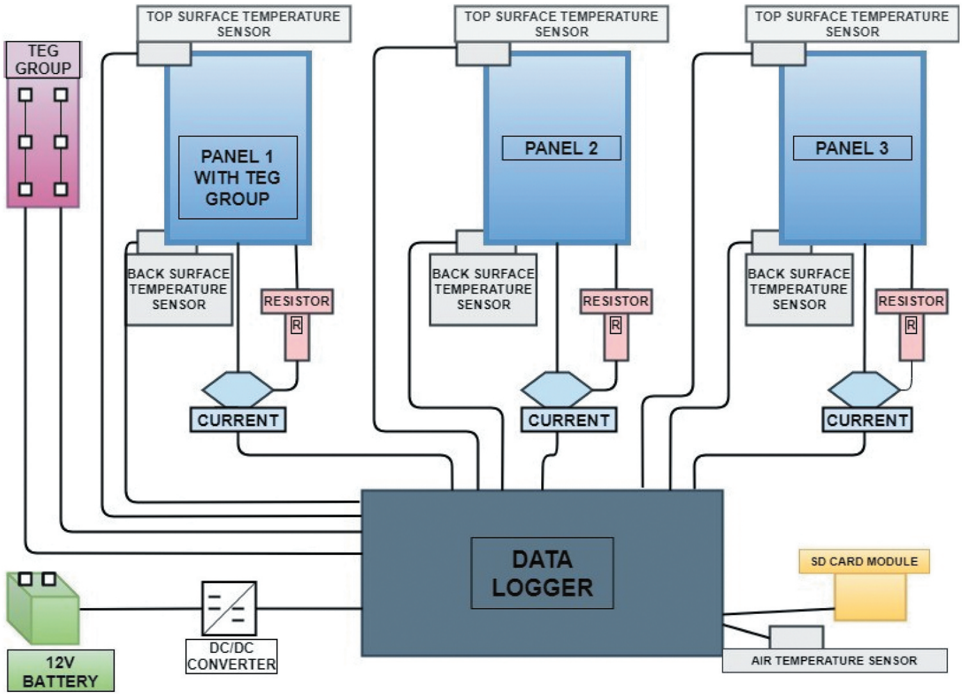

Figure 1. Design and circuit components of the system.

where $P_{TEG} = V_{TEG} \cdot I_{TEG}$ is the electric power generated by the thermoelectric generator. Input exergy of PV panel is the maximum exergy speed obtained from sunlight and can be calculated with the following equation (Hepbasli 2008).

$$\dot{E}x_{in} = I_s \cdot A \cdot \left[1 - \frac{4}{3} \cdot \frac{T_a}{T_s} + \frac{1}{3} \cdot \left(\frac{T_a}{T_s}\right)^4\right] \tag{11}$$

where T_s represents the temperature of the sun and its value is taken as 5777 K in the present study. Exergy efficiency can be defined as the ratio of useful exergy output to total exergy input (Petela 2003).

$$\eta_{ex} = \frac{\dot{E}x_{out}}{\dot{E}x_{in}} \tag{12}$$

Reorganizing Equation (12), exergy efficiency can be given as follows:

$$\eta_{ex} = \frac{V_{OC} \cdot I_{SC} + P_{TEG}}{I_s \cdot A \cdot \left[1 - \frac{4}{3} \cdot \frac{T_a}{T_s} + \frac{1}{3} \cdot \left(\frac{T_a}{T_s}\right)^4\right]} \tag{13}$$

Data collection

The amount of electrical energy obtained from photovoltaic panels varies depending on the climatic conditions in the field. The most significant factors affecting panel efficiency are radiation, wind speed, and ambient temperature. Two sample days were selected randomly from the months the study was conducted. The solar radiation change for these days is shown in Figure 2, the wind speed change in Figure 3, and the air temperature change in Figure 4.

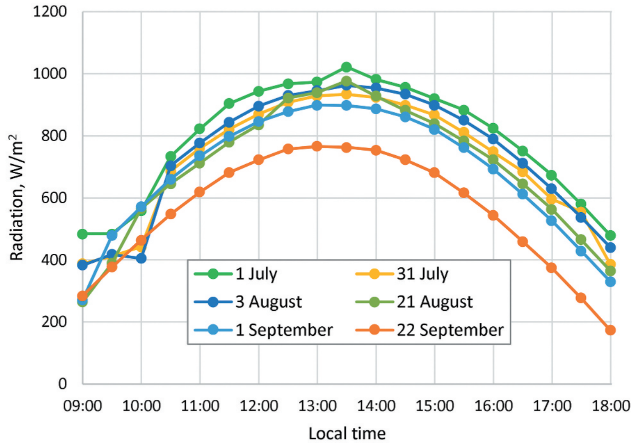

Figure 2. Sunlight in July, August and September.

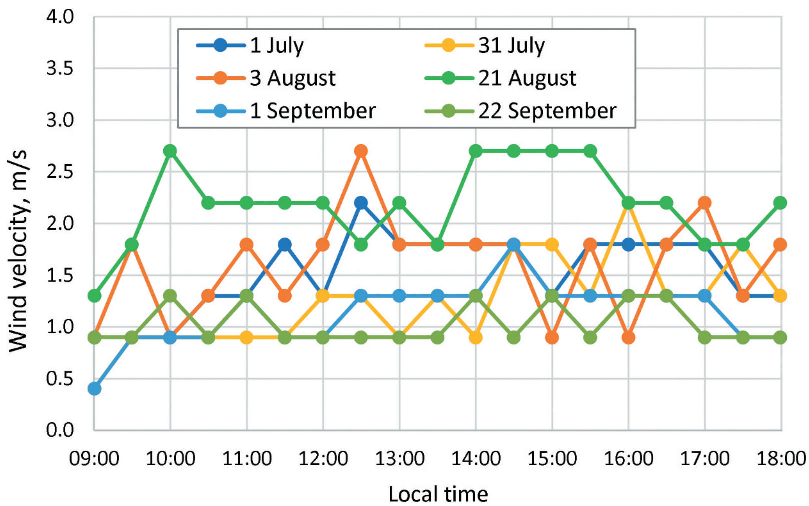

Figure 3. Wind speed in July, August and September.

Experimental setup

To examine the efficiency of photovoltaic cells used in electricity production from solar energy, 3 PV panels in the south direction of Trakya University campus are fixed on a carrier with 30° inclination and 0° azimuth angle (Figure 5). Technical information and features of the PV panels used are shown in Table 1. A software and hardware circuit has been designed that continuously measures and records the electrical energy produced from photovoltaic panels. The electrical power required to operate the system is supplied from the third panel in the experimental setup. However, when there is no solar radiation, there is a 12-volt battery in the circuit to receive uninterrupted data from the system. Other system components on the experimental setup are; a memory card, where the data is recorded, voltage sensors, current sensors, load resistors, temperature sensors, and connection cables that measure the electrical energy produced by PV panels and thermoelectric generators. The field climate data where the installation is made are recorded simultaneously from the Davis Vantage Pro2 Meteorology Station brand device. The features of these devices and sensors used in the system are shown in Table 2.

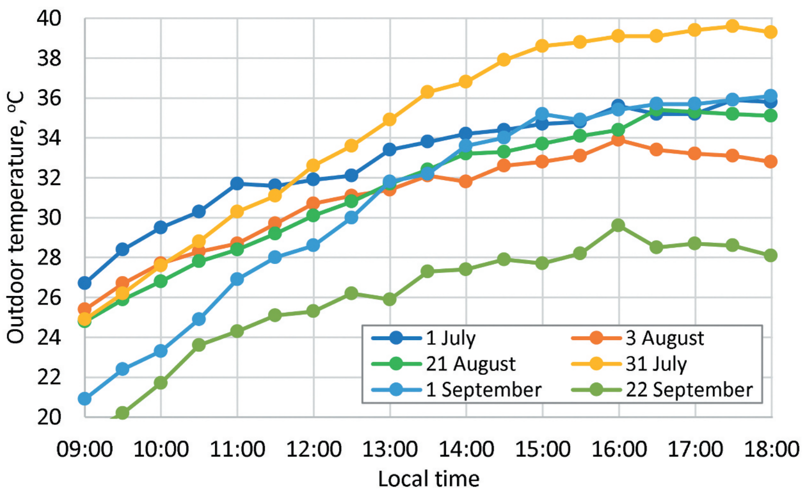

Figure 4. Air temperature in July, August and September.

Figure 5. Photovoltaic panel installation.

Table 1. Technical specifications of solar PV module.

Features	Value
Maximum Power (Pmax)	260 W
Power Tolerance	0~+3%
Maximum Power Voltage (V_{mp})	31.1 V
Maximum Power Current (I_{mp})	8.37 A
Open Circuit Voltage (V_{oc})	38.1 V
Short Circuit Current (I_{sc})	8.98 A
Nominal Operating Cell Temperature (NOCT)	45 ± 2°C
Maximum System Voltage	1000 VDC
Maximum Series Fuse Rating	15 A
Operating Temperature	−40°C~ + 8°C
Application Class	A
Weight	18.5 kg
Dimension	1650 × 992 × 40 (mm)

Table 2. Features of devices used in the data system.

Features	Error rate
Davis Vantage Pro2 Weather Station	±%0.5
DS18 B20 Temperature sensor	±%0.5
ACS712 Current sensor	±%1.5
0.47 Ω 25 W Load resistance	±%0.5
Atmega328P Software card	±2 LSB(Least Significant Bit)

After the installation is completed, the power output values of both PV panels and thermoelectric generators are measured and recorded from the beginning of July to the end of September. During July, August, and September, when the experiments were carried out, data were recorded at 10-minute intervals every day from 09:00 in the morning to 6:00 p.m.

Many methods are applied to cool thermoelectric materials. Due to their low costs and the absence of moving parts in the system, aluminum fins were used for this purpose. Figure 6 shows the technical sizes of aluminum fins, thermoelectric generators and Table 3 shows their features (https://html.alldatasheet.com/html-pdf/227422/ETC2/TEC1-12706/99/1/TEC1-12706.html).

As seen in Figure 7, aluminum fins are applied to cool the TEGs added to the back surface of the panel.

Electronic circuit elements and error rates used in the system are given in Table 2. In uncertainty analysis calculations of values taken from the system, voltage and current parameters affecting the power generation of photovoltaic panel are taken into consideration. Equation (14) can be used for this calculation:

$$U = \pm\sqrt{\left(\frac{\Delta V_{PV}}{V_{PV}}\right)^2 + \left(\frac{\Delta I_{PV}}{I_{PV}}\right)^2} \cdot 100 \qquad (14)$$

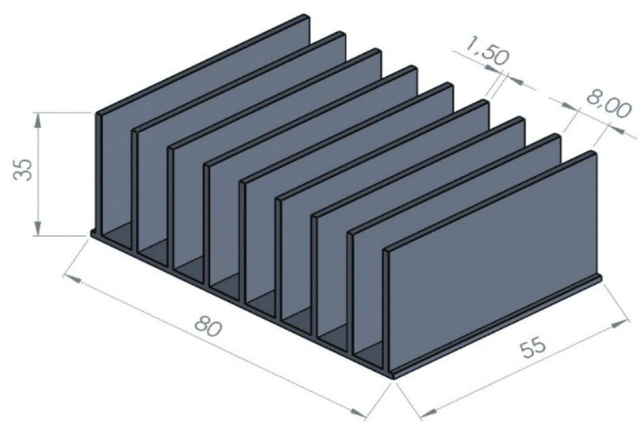

Figure 6. Aluminum fin cooler dimensions (mm).

Table 3. Thermoelectric materials technical features.

Hot Side Temperature (°C)	25	50
Qmax (Watts)	50	57
Delta Tmax(°C)	66	75
Imax (Amps)	6.4	6.4
Vmax (Volts)	14.4	6.4
Module Resistance (Ohms)	1.98	2.30

Figure 7. The assembly of aluminum fin and thermoelectric generators.

The error rate of voltmeter (ΔV_{PV}) and ammeter (ΔI_{PV}) are 1% and 1.3%, respectively. Total uncertainty for standard panel and thermoelectric generated panels are calculated as 3.92% and 3.94%, respectively.

Results and discussion

The results of experiments obtained from 2 different days of July, August and September showed that the best outcomes were taken from panels with thermoelectric generators in terms of energy efficiency as expected. As can be seen in Figure 8, energy efficiency in standard panel ranged between 6.32% and 12.99% on the first of July, while it was between 7.61% and 15.31% in the panel with the thermoelectric generator.

As can be seen in Figure 9, energy efficiency in standard panel ranged between 5.05% and 13.36% on 31st of July, while it was between 5.57% and 16.21% in panel with thermoelectric generator. Average energy efficiencies were 11.30% in standard panel and 12.99% in panel with the thermoelectric generator on 1st of July. Meanwhile, they were calculated as 11.30% in standard panel and 13.61% in panel with thermoelectric generator on 31st of July.

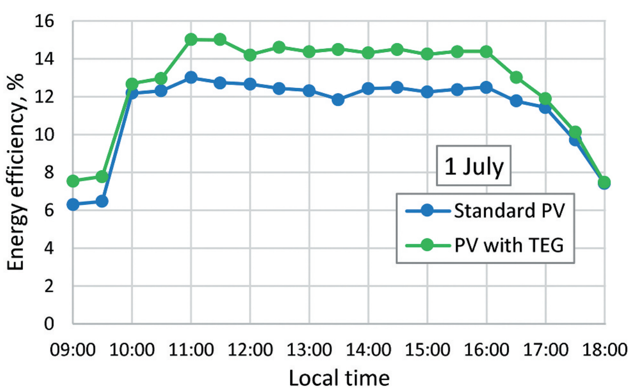

Figure 8. Energy efficiency on 1st of July.

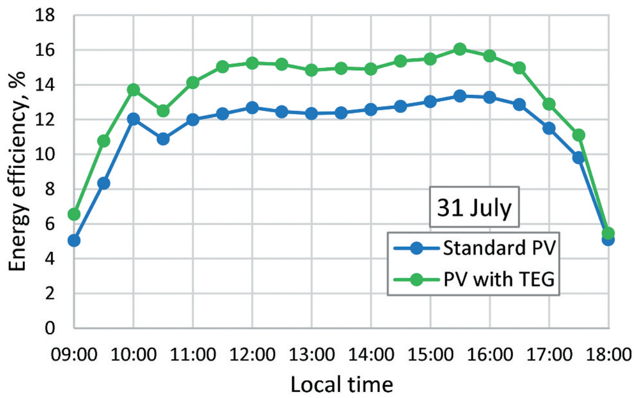

Figure 9. Energy efficiency on 31st of July.

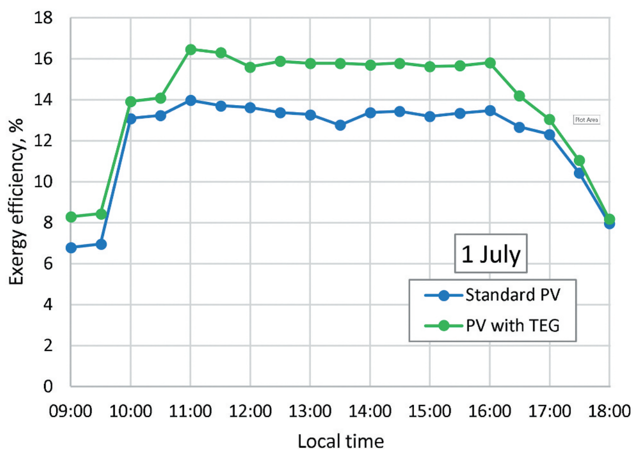

Figure 10. Exergy efficiency on 1st of July.

As can be seen in Figure 10, exergy efficiency in standard panel ranged between 6.79% and 13.98% on 1st of July, while it was between 8.19% and 16.46% in the panel with the thermoelectric generator. Average exergy efficiencies were calculated as 12.16% in a standard panel and 13.98% in panel with thermoelectric generator.

As can be seen in Figure 11, exergy efficiency in standard panel ranged between 5.42% and 14.39% on 31st of July, while it was between 6% and 17.47% in panel with thermoelectric generator. Average exergy efficiencies were calculated as 12.17% in a standard panel and 14.65% in panel with thermoelectric generator.

As can be seen in Figure 12, energy efficiency in standard panel ranged between 6% and 13.21% on 3rd of August, while it was between 6.22% and 14.87% in panel with thermoelectric generator. Average energy efficiencies on this date were calculated as 11.34% in standard panel and 12.64% in panel with thermoelectric generator.

As can be seen in Figure 13, energy efficiency in standard panel ranged between 6.25% and 14.26% on 21st of August, while it was between 7.13% and 15.71% in panel with thermoelectric generator. Average energy efficiencies on this date were calculated as 11.95% in standard panel and 13.29% in panel with thermoelectric generator.

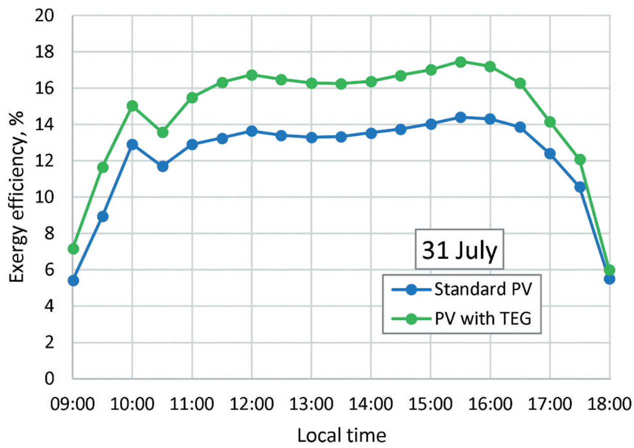

Figure 11. Exergy efficiency on 31st of July.

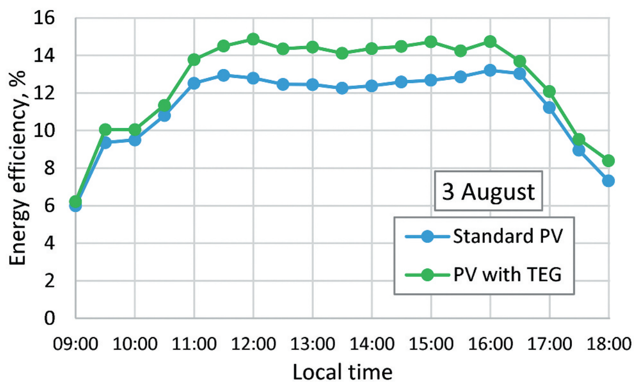

Figure 12. Energy efficiency on 3rd of August.

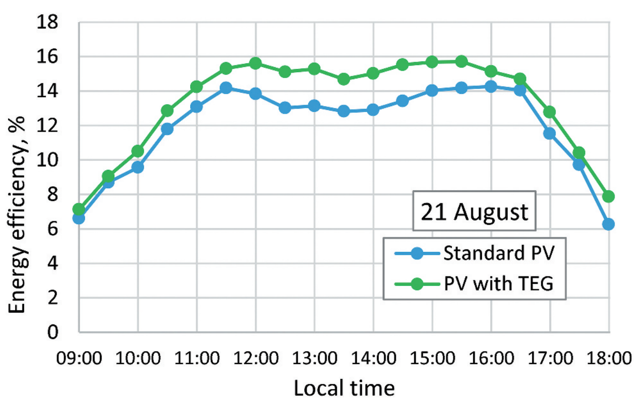

Figure 13. Energy efficiency on 21st of August.

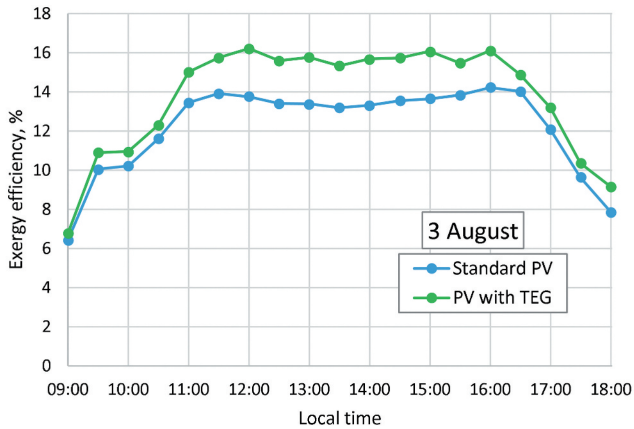

Figure 14. Exergy efficiency on 3rd of August.

As can be seen in Figure 14, exergy efficiency in standard panel ranged between 6.44% and 14.22% on 3rd of August, while it was between 6.78% and 16.22% in panel with thermoelectric generator. Average exergy efficiencies on this date were calculated as 12.19% in standard panel and 13.75% in panel with thermoelectric generator.

As can be seen in Figure 15, exergy efficiency in standard panel ranged between 6.73% and 15.35% on 21st of August, while it was between 7.77% and 17.11% in panel with thermoelectric generator. Average exergy efficiencies on this date were calculated as 12.86% in standard panel and 14.47% in panel with thermoelectric generator.

As can be seen in Figure 16, energy efficiency in standard panel ranged between 3.56% and 14.82% on 1st of September, while it was between 3.69% and 16.31% in panel with thermoelectric generator. Average energy efficiencies were calculated as 11.81% in standard panel and 13.24% in panel with thermoelectric generator.

As can be seen in Figure 17, energy efficiency in standard panel ranged between 2.01% and 15.87% on 22nd of September, while it was between 2.13% and 17.29% in panel with thermoelectric generator. Average energy efficiencies on this date were calculated as 12.19% in standard panel and 13.30% in panel with thermoelectric generator.

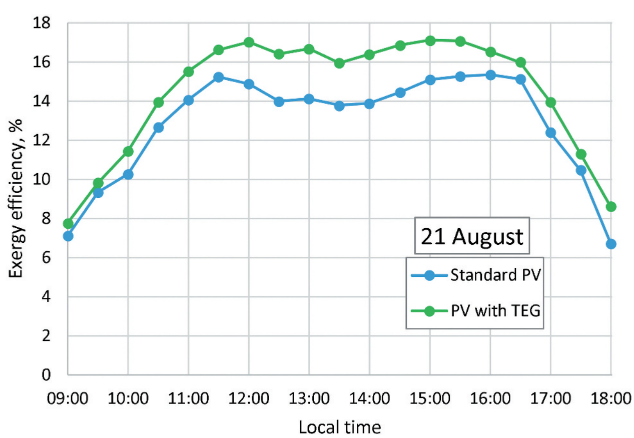

Figure 15. Exergy efficiency on 21st of August.

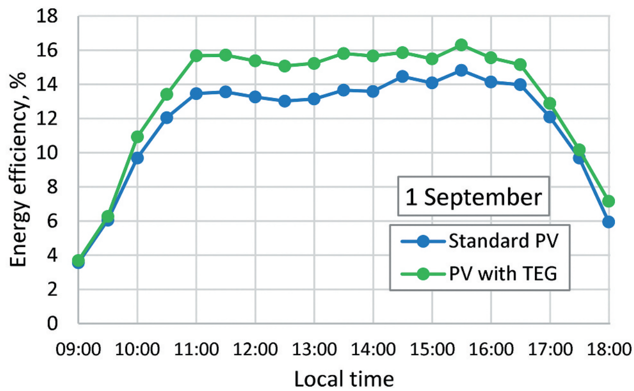

Figure 16. Energy efficiency on 1st of September.

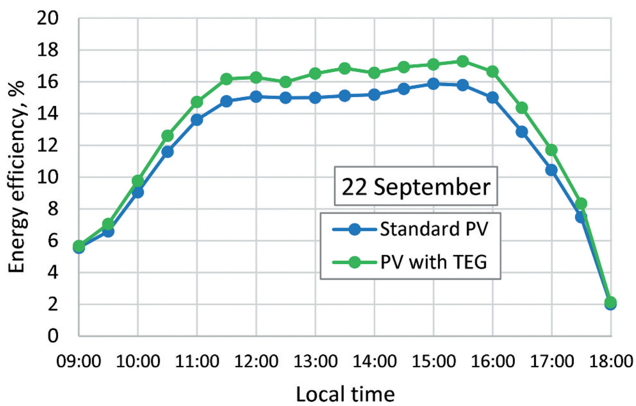

Figure 17. Energy efficiency on 22nd of September.

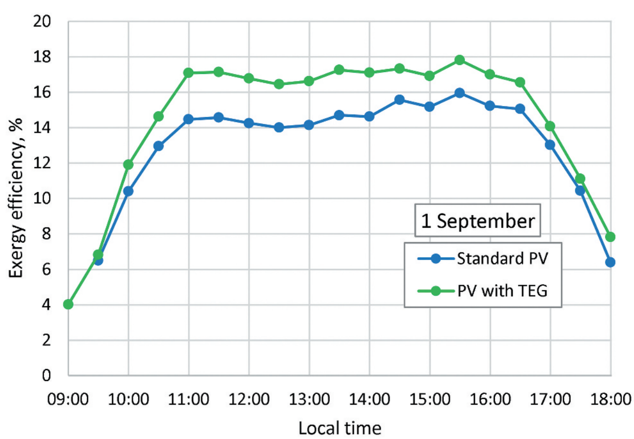

Figure 18. Exergy efficiency on 1st of September.

As can be seen in Figure 18, exergy efficiency in standard panel ranged between 3.82% and 15.96% on 1st of September, while it was between 4.02% and 17.82% in panel with thermoelectric generator. Average exergy efficiencies were calculated as 12.70% in standard panel and 14.45% in panel with thermoelectric generator.

As can be seen in Figure 19, exergy efficiency in standard panel ranged between 2.16% and 17.05% on 22nd of September, while it was between 2.32% and 18.85% in panel with thermoelectric generator. Average exergy efficiencies on this date were calculated as 13.09% in standard panel and 14.49% in panel with thermoelectric generator.

Effect of temperature on the power output of PV panels and TEGs

As seen in Figure 20 that shows the output power of the modified PV panel and the standard PV panel, after 11 am, despite the higher temperature of the panel with TEG (more than 70 degrees), there is higher output power, compared to the standard panel which has even lower temperatures. This trend

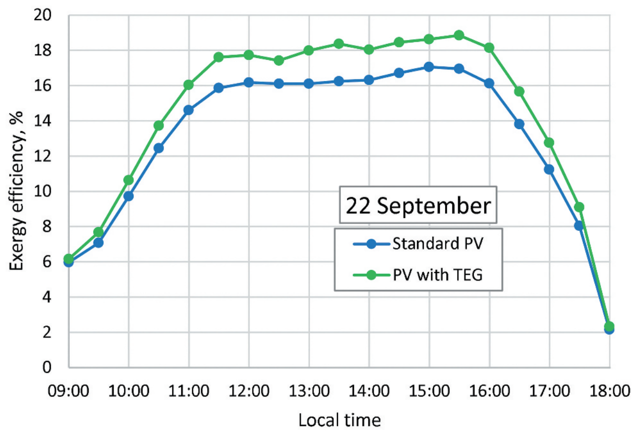

Figure 19. Exergy efficiency on 22nd of September.

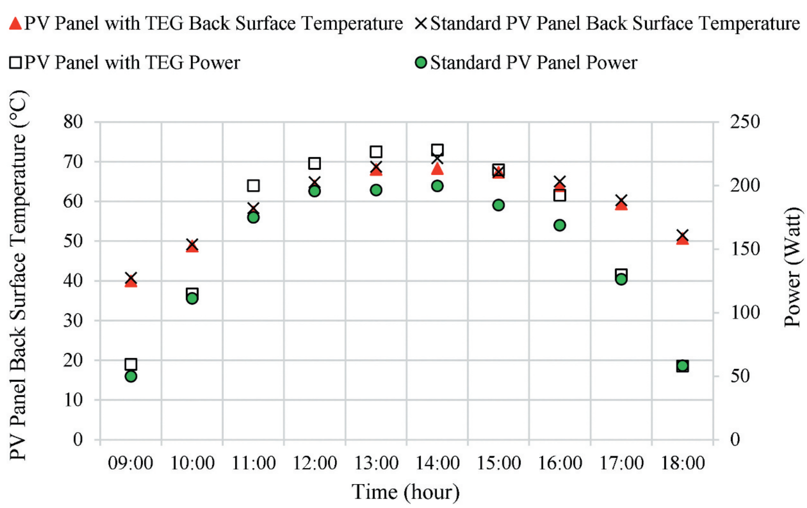

Figure 20. The effect of PV surface temperature variations on July 1st PV panel power output.

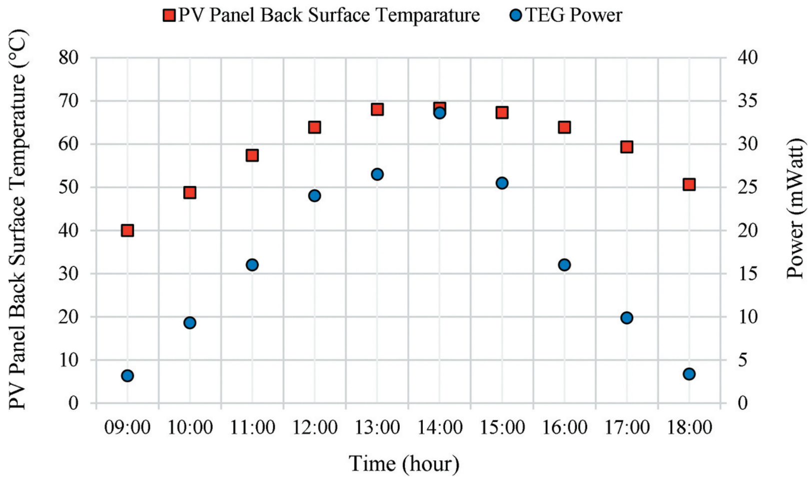

Figure 21. The effect of PV surface temperature variations on July 1st TEGs power output.

is valid till 5 pm as can be seen in Figure 20. Figure 21 shows the effect of PV panel surface temperature variations on July 1st on the power output of PV panels and TEGs. By increasing and decreasing the surface temperature, the output power also decreases or increases, accordingly.

Figures 22 and 23 show the effect of PV panel surface temperature variation on August 3rd on the power output of PV panels and TEGs. As mentioned above, Figure 22 shows the higher output for the modified panel, regardless of its higher temperature in August again, Figure 23, depicts the power and temperature variations of both panels for August 3rd.

For 1st September, the behavior is shown in Figures 24 and 25. Same as before, the effect of PV panel surface temperature variations on the power output of PV panels and TEGs proves the advantage of using the cooling effect on the obtained power.

Total Energy Amounts Generated by PV Panels According to Months

Table 4 shows the energy amounts obtained from the standard PV panel and the PV panel with a thermoelectric generator in July, August and September. Applying a thermoelectric generator to a solar PV panel ensured obtaining 10.29%, 7.14%, and 7.09% more electrical energy

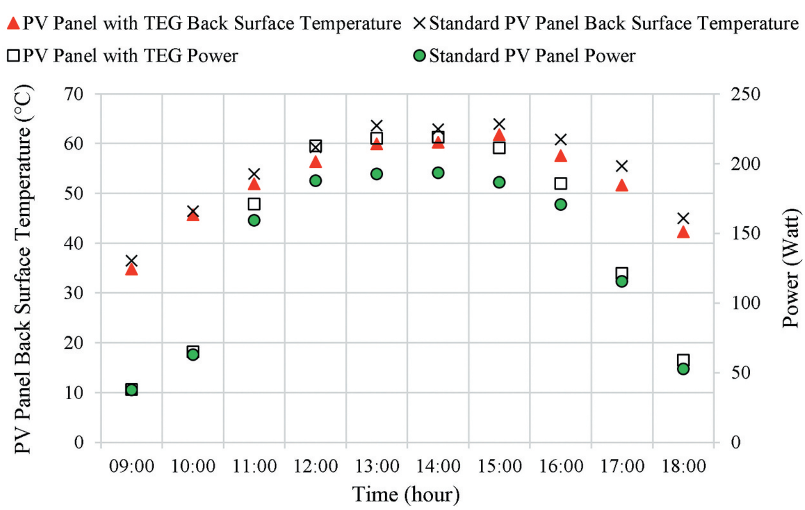

Figure 22. The effect of PV surface temperature variations on August 3rd PV panel power output.

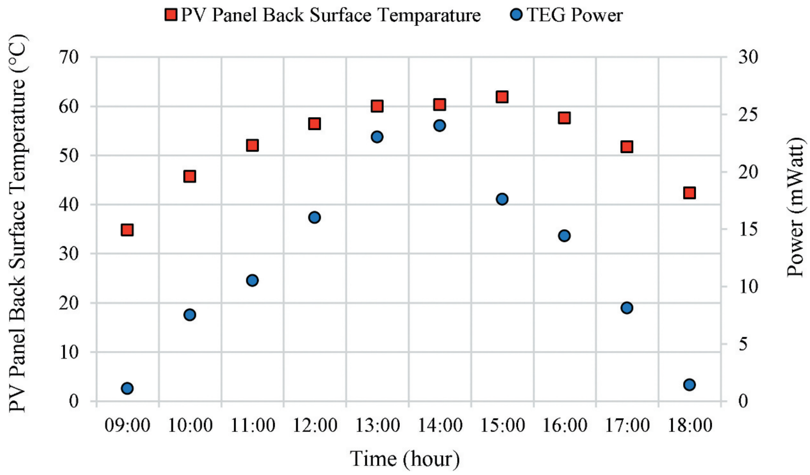

Figure 23. The effect of PV surface temperature variations on August 3rd TEGs power output.

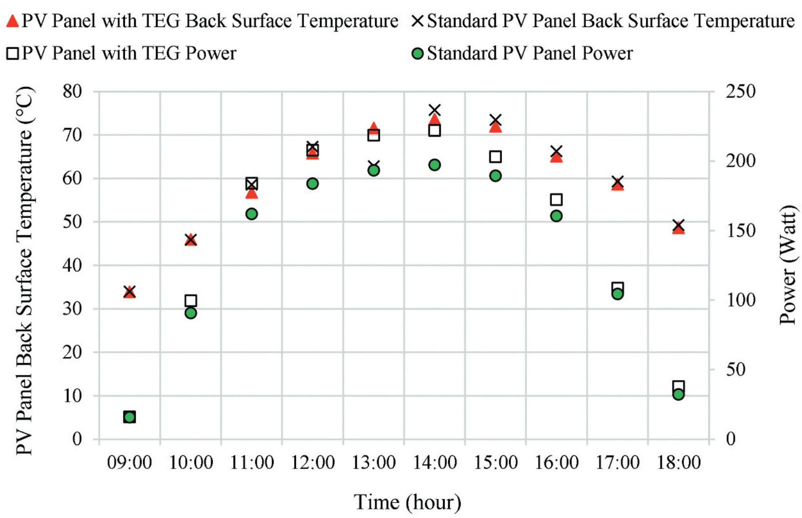

Figure 24. The effect of PV surface temperature variations on September 1st PV panel power output.

than standard PV panels in July, August, and September, respectively. Sum of energy generetated throughout the experimental period were 100402.70Wh and 108762.97Wh for the standard PV panel and the PV panel with the thermoelectric generator, respectively. Compared to standard PV panel, an average of 8.4% more electricity energy was obtained from the PV panel with thermoelectric generator.

Conclusions

In this study, the losses in energy production due to the increase in temperature in the PV panels, especially in the summer months, were reduced by TEG application. An increase in the PV Panel output power was achieved. According to the results obtained;

- More electrical energy was produced in the PV panel with a thermoelectric generator in July, August, and September when the experiments were carried out.

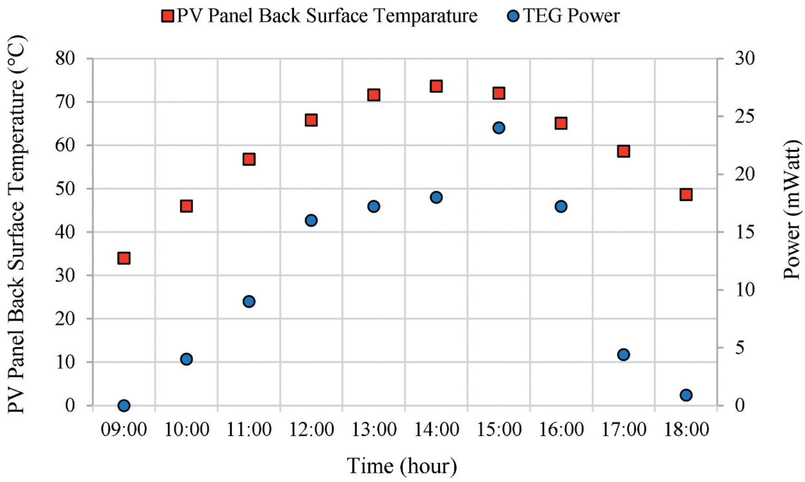

Figure 25. The effect of PV surface temperature variations on September 1st TEGs power output.

Table 4. Total energy amounts generated in PV panel according to months.

Energy Amounts Generated According to Months	Standard PV (Wh)	PV with TEG(Wh)	Difference (%)
July	38259.81	42197.38	10.29
August	32678.15	35012.83	7.14
September	29464.74	31552.76	7.09
July/August/September Total	100402.70	108762.97	8.33

- With the application of a thermoelectric generator in the PV panel, an average of 8.4% more electrical energy was obtained per month. This indicates that when the number of PV panels combined with TEG is increased, the total energy could increase significantly.
- The output power of TEGs also increases depending on the rise in air temperature and PV panel surface temperature.
- Since the average temperature was higher in July, maximum energy was produced in the thermoelectric generator panel. Compared to the standard panel, the PV panel, in which a thermoelectric generator is applied, had 10.29% more electricity in July, 7.15% in August, and 7.09% more in September, respectively.

Depending on the results obtained from this study, some improvements should be made to the system as following;

- If it is desired to increase the amount of additional electricity produced by thermoelectric generators by utilizing the PV panel temperature, the temperature difference between the surfaces of the thermoelectric generators should also be increased. In our application, the temperature difference between the surfaces of the thermoelectric generators could be increased to a maximum of 16°C, according to the field climatic conditions. When this difference is enriched with different cooling methods, more additional electrical energy will be obtained.
- In cases where the temperature is high on the bottom surface of the PV panel, the electrical current values produced by the thermoelectric generators are measured instantaneously with the constant load resistance in the circuit. However, to calculate the electric current values produced in thermoelectric generators when the temperature is low on the bottom surface of the PV panel,

the load on the circuit must be designed with variable resistance. Under current conditions, such a ready-made circuit has not been found. If the deficiencies mentioned are eliminated in future studies, the system's efficiency will be increased even more.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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Nomenclature

PV	Photovoltaic
G	Solar irradiation (W/m^2)
I	Electrical current (A)
V	Voltage (V)
I_c	TEG supply current (A)
P	Power (W)
τ	Transmissivity
α	Absorptivity
TEG	Thermoelectric Generator
ZT	Dimensionless figure of merit
Q_{in}/A	Heat flux density (mW/cm^2)
T_h	Hot-side temperature (K)
T_c	Cold-side temperature (K)
R_c	Electrical contact resistance
ρ_c	Contact resistivity ($\Omega \cdot m^2$)
σ	Electrical conductivity (S/m)
S	Seeback coefficient (μV/K)
A	Surface area (cm^2)
η	Efficiency (%)
k	Thermal conductivity (W/m·K)
FF	Fill factor
$Ɇ_{solar}$	Solar radiation energy (W)
$Ɇ_{out}$	Energy output (W)
$Ɇ_{in}$	Energy input (W)
$Ɇx_{out}$	Exergy output (W)
$Ɇx_{in}$	Exergy input (W)
$Ɇx_{elec}$	Electrical exergy (W)
P_{TEG}	Power generated by thermoelectric generator (W)

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