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Research Article

Effect of module operating temperature on module efficiency in photovoltaic modules and recovery of photovoltaic module heat by thermoelectric effect

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ABSTRACT

One of the parameters affecting the efficiency of photovoltaic (PV) modules and PV systems is the temperature. The factors that increase the temperature in PV modules cause loss of efficiency. In this study, experiments have been conducted with the aim of reducing the module temperature. For this purpose, four polycrystalline and four monocrystalline PV modules, all with the same features, were used. A pair of polycrystalline and monocrystalline modules were used as reference modules. The aim of this study is to reduce the operating temperature of the modules, while also decreasing the transient temperature fluctuations in the system, in order to prevent the loss of efficiency. For this reason, current, voltage and power values of PV modules have been examined and the relationship between these values and module temperature has been explained. As a result, temperature values were measured at 30-80°C in reference modules, 30-50°C in heat pipe modules, 30-37°C in modules using heat pipes and phase-changing material, and 30-66°C in modules using phase-changing material with flexible surfaces. If the PV module operating temperature is increased by 35°C, the module efficiency decreases by 10%. Heat pipe and PCM balance the temperature in PV/T/PCM monocrystalline and polycrystalline modules. In PV/T/PCM modules, efficiency loss caused by temperature increase is 1%. In addition, electrical energy is produced from the heat accumulated on the surface of the PV module by means of Thermoelectric Generator (TEG). When the temperature difference between the surfaces is 15°C, the naturally cooled TE provides 0.45V energy output, while the forced-cooled TEG provides 0.97V energy output. As the temperature gap between the surfaces increases, the voltage and current values of the TEG also increase. Briefly, TEG's power values increase up to 5W depending on the temperature gap between surfaces.

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INTRODUCTION

Fossil fuels, which are exhaustible, are energy sources with high CO_2 emissions. Global warming forces researchers to find an alternative for fossil fuels and increase energy efficiency [1]. Natural disasters have started to occur very frequently due to the climate changes in the world. Despite this situation, according to International Energy Agency (2017) data, fossil energy sources supply 81% of global energy demand [2]. The need for energy resources together with the ever-worsening environmental problems in the world, have become a common problem concerning the entire humanity. For this reason, extensification of the renewable energy resources, developments in technological fields and their efficient use are amongst the leading problems of humanity.

The output power and efficiency of solar cells decrease by about 10% due to the increase in module temperature [3]. Since the dark-colored surfaces of the solar cells are heat-retaining, the surface temperature of the modules can reach up to (80°C). As the temperature of the module increases, the module tension decreases in the P-V characteristic. Since the PV modules have been adversely affected by the temperature, the output voltage and power of the module decrease as the temperature increases. As the solar radiation increases, the module voltage and module current increase. In addition to the effect of temperature, the efficiency of PV systems is negatively affected by other parameters, such as shading, dusting and reflection [4]. Electricity production with PV is increasing in the world. While the contribution of PV technology to total energy production was 2.1% in 2017, it increased in 2018 and became 2.58%. Researchers argue that PV power generation will reach up to 30-50% of total global energy production by 2050. The parameters that affect the efficiency of PV technology, which is ever increasingly contributing to the total energy production, is an important matter that needs to be focused on and improved [5,6].

The PV capacity of EU countries is between 470 kWh and 1390 kWh [7]. In the Mediterranean region, including Turkey, it is between (1100-1330) kWh [8]. France and Austria have medium potential, between (800-1000) kWh. Countries like Northwest Europe, England, and Denmark have low potential with (700-800) kWh. Northern Sweden and Finland are below 700 kWh. Turkey has an average duration of 2737 hours/year daylight due to its location, [9]. This research was conducted in Kayseri province. The solar map of Turkey and Kayseri is given in (Figure 1). The Kayseri province has an average solar radiation of 4-5 kWh/m²-day. Daily insolation time in Kayseri province is 13 hours on average during summer.

Radiation intensity is the main energy source of PV modules. Therefore, power generation is directly related to the intensity of radiation reaching to the module surface. [11. 12] While solar cells generate electrical energy, the temperature of the modules increases [13]. One of the most important factors of efficiency loss in modules is the increased surface temperature due to environmental temperature and solar radiation [14]. Wongwuttanasatian et al., claims that one degree increase in cell temperature can result in efficiency loss of 0.04% to 0.065%. Parameters

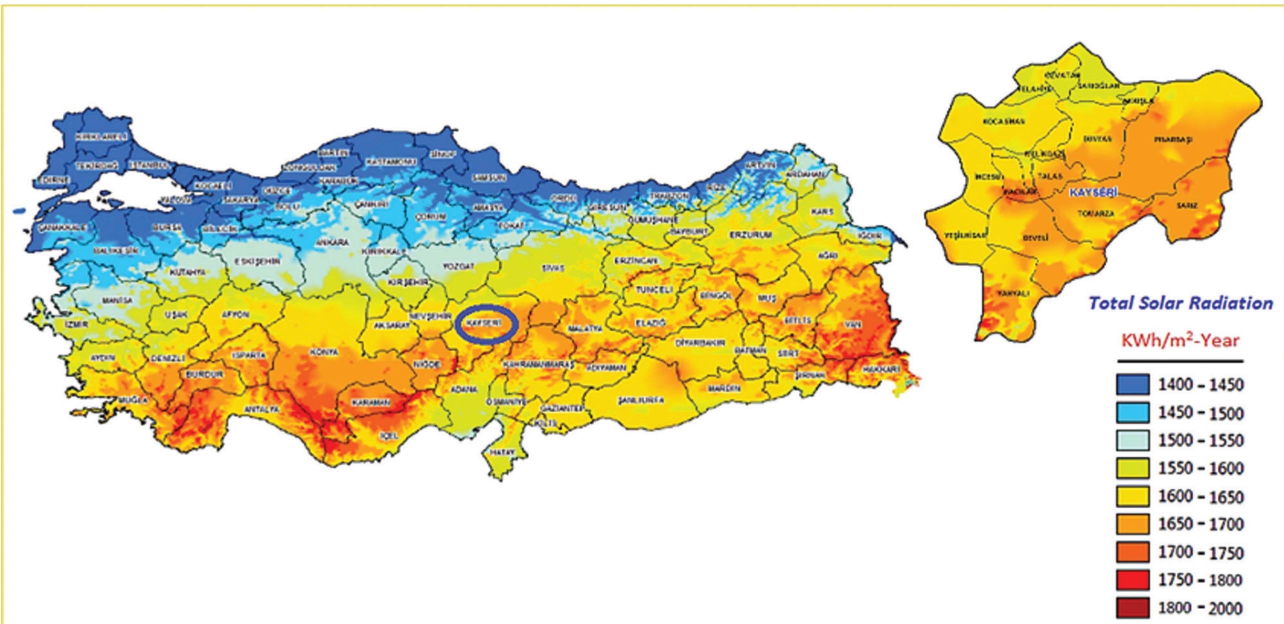

Figure 1. Turkey - Kayseri province solar energy potential [10].

Table 1. Electrical and physical properties of PV modules

PV Module Features	Monocrystalline Module	Polycrystalline Module
Maximum power (P_{max})	10 W	10 W
Open circuit voltage (V_{oc})	21.6 V	21.6 V
Short circuit current (I_{sc})	0.61 A	0.61 A
Max. power current (I_{mp})	0.56 A	0.56 A
Max. System Voltage (DC)	600 V	600 V
Module Efficiency (%)	15.15%	15.15%
Type of cell	Monocrystalline	Polycrystalline
Dimensions / Frame	(355×305×20) mm/Aluminum	(355×305×20) mm/Aluminum
Weight	1.5kg	1.5kg

Table 2. Features of measuring devices and uncertainty analysis

Device Name	Measuring Type	Measurement Unit	Efficiency (%)	Measured Efficiency (%)	Percentage Rate
PV Modules					
SCN100	Temperature	ºC	0.2	25	±1.03
Thermocouple	Temperature	ºC	0.2	25	±0.28
Pyranometer	Radiation	W/m²	±1.5	1000	±1.51
Multimeter	Voltage	V	±1.2	19,40	±1.21
Ammeter	Current	A	±1.2	0,495	±2.16

such as the material composition of the modules, radiation intensity, environmental temperature and module temperature affect the efficiency of the modules. Decrease in surface temperatures leads to an increase in PV performance [15]. Gedik et al. claims that when the PV module surface temperature is increased by 14.9°C, the module efficiency decreases to 10.7% from 12.07% [16].

The temperature increase has a negative effect on PV cells. For Thermoelectric Generator (TEG), the temperature difference affects the conversion efficiency of generators positively. It is reported that combining the PV/TEG system is an ideal way to increase the system's efficiency [17]. The usage of solar energy as a source in hybrid systems is an important parameter that significantly determines the system efficiency.

Two types of cooling methods are used to increase the efficiency of PV modules. Energy consuming (active) cooling is natural energy consuming (passive) cooling [18]. PCM (phase changing material) can be used on the surface to keep the PV module temperature at 25°C. The melting point of PCM must be higher than the ambient temperature [19]. The heat pipe concept can be applied by placing copper pipes and aluminum fins on the back surface of PV modules. It is reported that these applications can keep the PV surface temperature (20-100) W/cm² in solar radiation at 40°C [20]. The PV module temperature can be reduced by using an active cooling system. When the active cooling system is used, module efficiency increases by 10% [21]. For higher efficiency in PV modules, the module surface must be cooled. While proper cooling increases the electrical efficiency, it reduces the cell breakdown rate and extends the life of PV modules [22].

When PCMs are exposed to heat, their internal energy starts to increase. If their internal energy continues to increase, the temperature of the substance reaches up to the phase change temperature. If the heat is continuously supplied to PCM, phase change occurs at a constant temperature. While latent heat is stored in phase change, the temperature of the substance remains constant. If heat is applied to the liquid PCM, its temperature starts to rise. This situation continues until the evaporation temperature is reached.

Adding fins to air-cooled PV modules reduces the average temperature. When solar radiation is (895-900) W/m² and ambient temperature is (20-33.4) °C, increasing the air flow rate improves cooling and PV performance [23]. Finned, corrugated and tubular surfaces can be added to the back of the PV modules for passive cooling. If PCMs are connected to finned coolers, module efficiency increases [24]. On finned surfaces, the module efficiency increases from 5.33% to 9.82%, while its performance increases from 0.63 to 0.66 (4.8%) [24]. The PCM chosen for the PV modules can reach the heat storage capacity expected from the system [25]. PCMs are classified as organic, inorganic and eutectic. It is reported that inorganic substances per unit volume have more than twice the heat storage capacity of organic substances [26]. PCMs can be used for PV and hybrid systems. Keeping the PV system close to the test conditions reduces the efficiency loss. Mohamet et al. claims that when PCM is used in PVs, modules can be kept at 30°C [27].

An extensive literature search indicates that factors which increase the temperature in photovoltaic modules cause efficiency loss. Because of this, reducing the operating temperature of the modules as well as the transient temperature fluctuations in the system is aimed in this study. For this purpose, an experimental condition has been carried out, by using four polycrystalline and four monocrystalline photovoltaic modules with the same features. One polycrystalline and another monocrystalline module were used as reference modules. In this study, the output parameters of the PV modules were examined in detail.

THEORY

In the experiments, PV, PV/T, PV/T/PCM and PV/PCM modules were operated under exact same conditions. Copper pipes were added to the system as heat pipes, to absorb the heat accumulated on the surfaces in PV/T, PV/T/PCM modules. Forced (pressured) water circulation was performed to prevent the heat accumulation. The energy required for the pressured water circulation is met from the system. The water circulating in the system carries the heat received from the modules to the surface of the TEG. There are 4 monocrystalline and 4 polycrystalline modules in the system. The power of the modules used in the system is 10W. The physical properties of the modules are the same. According to the test data of the modules, the efficiency of the modules is found to be 15.15% while open circuit voltage is 21.6V and short circuit current is 0.61A (Table 1).

The uncertainty analysis of the measuring devices used in the experimental setup was performed. Thus, an error rate of the measuring devices was determined and shared in (Table 2). Error values in standard test conditions were used in the uncertainty analysis. Results indicate that error rates are higher than standard test conditions. According to the results, it was predicted that errors may present in the rates given as %. Error rates are at an acceptable level.

Thermal energy storage methods are preferred so that the heat energy may be used as needed. As known, the controlling transient temperature changes and temperature control is possible with thermal energy storage methods. In this study, Calcium Chloride Hexahydrate ($CaCI_2 \bullet 6H_2O$) is used as PCM in the system to store thermal energy. Under ambient temperature conditions (25°C), when PCM, which is in the solid phase, is exposed to heat in the system, begins to melt at 29.7°C. During the solid-liquid phase change, its heat holding capacity is 171 kJ/kg.

$$\eta_h = \eta_{stk}[1 - \beta(T_h - 25)] \quad (1)$$

In the equation (2), (η_h) is cell efficiency, (η_{stk}) is efficiency under test conditions, (T_h) is cell temperature, and (β) denotes cell temperature coefficient. Module efficiency that depends on the cell temperature, can be calculated with the following equation.

$$n_m = \eta_h * \tau_g * \alpha_h * PF \quad (2)$$

In the equation (3), (τ_g) is the permeability coefficient of the module, (α_h) is the absorption rate of solar radiation and (PF) is the packing factor. The maximum power obtained from the module is calculated as follows.

$$P_{max} = FF * V_{oc} * I_{sc} = I_{mp} * V_{mp} \quad (3)$$

(FF) is the filling factor given in equation.

$$FF = \frac{V_{mp} * I_{mp}}{V_{oc} * I_{sc}} = \frac{P_{\max}}{V_{oc} * I_{sc}} \quad (4)$$

(V_{mp}) is the maximum voltage (V), (V_{oc}) is the open-circuit voltage (V), (I_{mp}) is the maximum current (A) and (I_{sc}) is short circuit current (A).

The electrical gain ($\dot{E}_{net}$) obtained from the PV module can be calculated using the following equation.

$$\dot{E}_{net} = n_m * A_m * I(t) \quad (5)$$

In the equation (6), (n_m) is module efficiency and (A_m) is the module surface area (m²). The following equation is used to find the total power that can be obtained from a PV module.

$$P_m = P_{stk}[1 - \beta(T_h - 25)] \quad (6)$$

Module power under test conditions is denoted by ($P_{stk} = P_{max}$) and the cell temperature (°C) is denoted by (T_h) under operating conditions.

The annual power obtained from the module is calculated by using the following equation;

$$P_{yıl} = P_m * GS_{ort} * \eta_{inv} * 365 \quad (7)$$

In the equation (7), (P_m) is installed power (kW), (GS_{ort}) is the annual average insolation duration (hour) and (η_{inv}) (%) is the inverter efficiency.

If the temperature difference is created by giving heat to the contact points of two semiconductors made up of different materials, an electrical voltage occurs at the ends. The voltage occurring in the conductors is called the "Seebeck voltage". Generators can be made using the Seebeck effect in semiconductors. P power or I current obtained from TE module varies according to the thermal, electrical, and dynamic properties of the TE module. The current of the TE module can be calculated by measuring the temperature values on its voltage surface. The voltage of the TE module is directly proportional to the temperature difference between semiconductor surfaces [28].

The open circuit voltage, formed from two different semiconductor materials, can be derived from the following equation;

$$V = \alpha * \Delta T \tag{8}$$

In the equation (9), (α) is the Seebeck coefficient (V/K) and (ΔT) is the temperature difference between the surfaces in the pair (ΔT = T2-T1) in Kelvin.

$$\alpha = \alpha 1 - \alpha 2 \tag{9}$$

The properties of the semiconductors that made up the circuit determine the value of (α). When a charge is connected to the TE module, its voltage (U) drops. The current (I) passing through the circuit is expressed by the following equation;

$$\mathrm{I} = \frac{\alpha \Delta T}{R_{in} + R_L} \tag{10}$$

In the given equation, (R_{in}) is the mean internal resistance of the TE module (Ω) and (R_L) is the load resistance. If the load resistance is equal to the module internal resistance, the maximum power can be drawn from the TE module.

Experiments were conducted in the Kayseri province in Turkey. System data were recorded for one year. Modules used in the system and their applications are shown in Figure 2, in which PV monocrystalline and polycrystalline modules are the referring modules. Heat pipes were applied to PV/T monocrystalline and polycrystalline modules. PV/T/PCM monocrystalline and polycrystalline modules were the insulated modules with PCM applied on their surfaces and a heat pipe passed through them. PV/PCM monocrystalline and polycrystalline modules were the modules with PCM applied on their surface in silicon.

The PCM was fixed on the backside of the panel by using the capsule method, thus, encapsulating it in two layers with a total of 760 ml passing through the heat pipe. The outer surface of PCM was covered with XPS thermal insulation material. Design of the experimental system is given schematically in (Figure 3).

As seen in Figure 3, module temperatures are measured from points (1-4,7-10) in the system with a K-type thermocouple. MPPT charge regulator temperature, battery temperature and ambient temperature are also measured with a K type thermocouple (5-6-12). Module outputs are connected to the charge regulator via a switch. Output data of 8 modules in total are monitored through the system. The charge regulator output is connected to the DC lamp and the charge output is connected to the gel battery. The system works independently from the network.

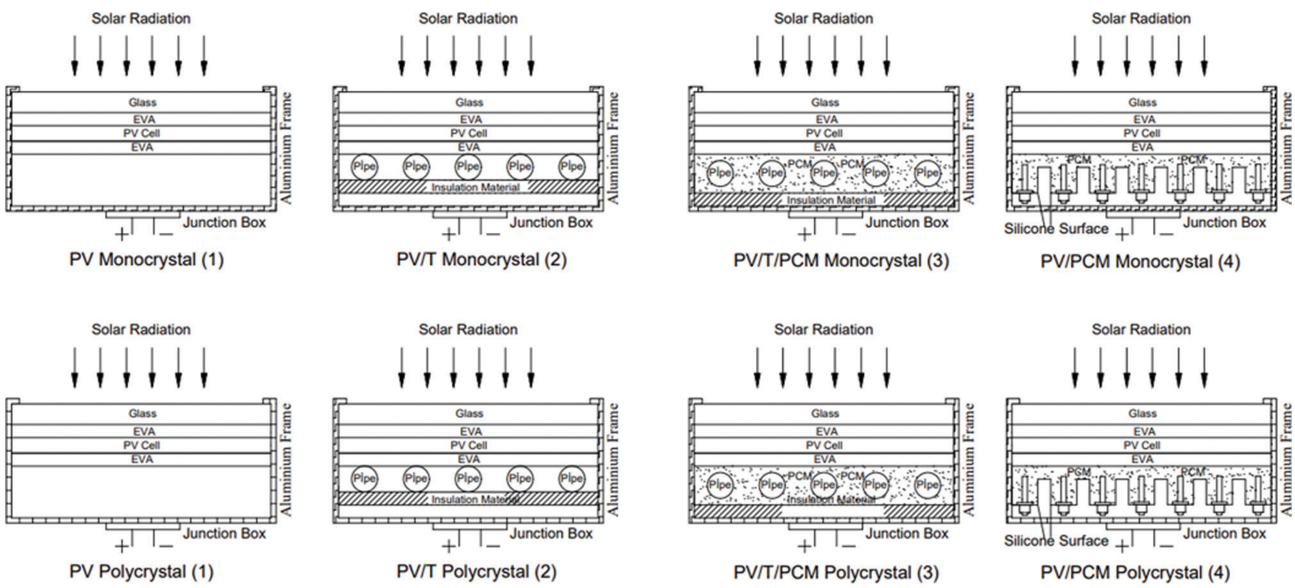

Figure 2. Modules used in the system and their applications.

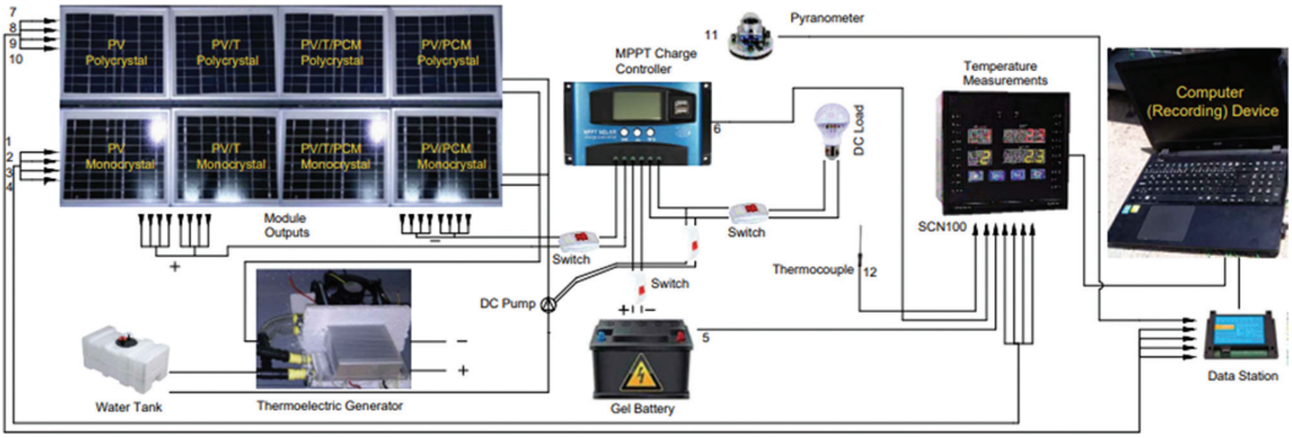

Figure 3. Design of the experimental system.

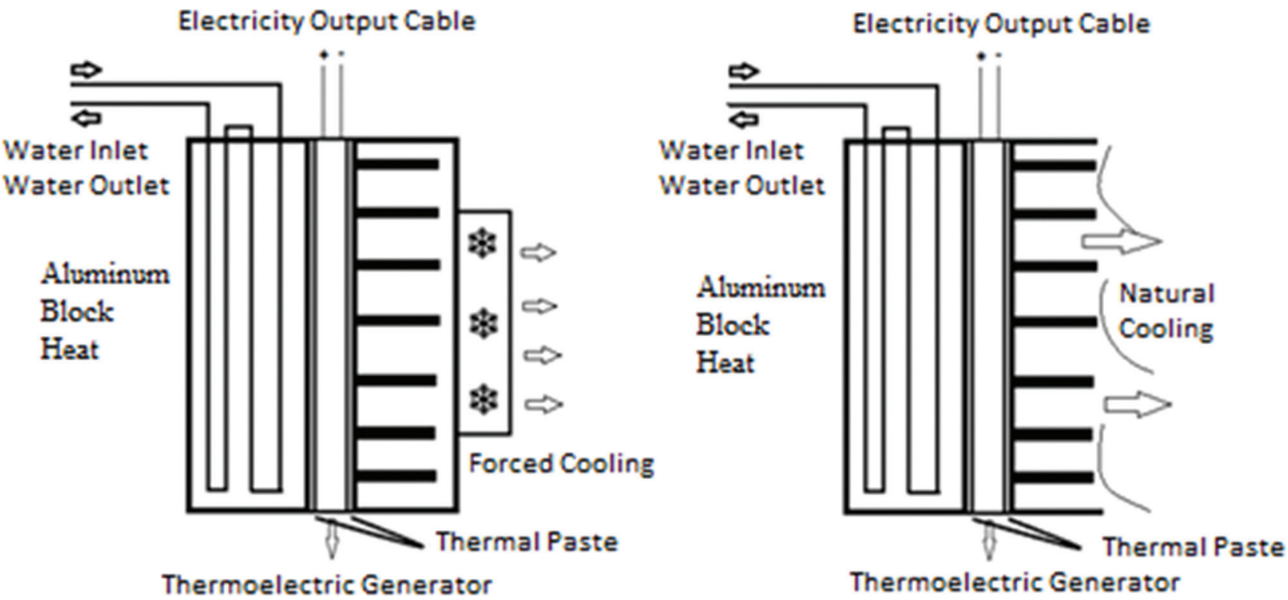

Figure 4. Forced and atmospheric cooled thermoelectric generator.

Polycrystalline and monocrystalline PV/T, PV/T/PCM modules send the water taken from the tank to the heat pipe forcefully, using a DC pump. The circulation pump is activated when the module temperature starts to rise. When the temperature of the PV/T modules is equivalent to the conventional modules, circulation is stopped. Hot fluid obtained from the PV modules is sent to the TEG system. In the TEG system, the temperature difference provided on the TE module surfaces is used in order to generate electrical energy. TEG output data are measured by multimeters. Radiation values are observed by means of pyranometer (11) in (Figure 3).

In the system, the heat source for TEG is PV/T modules. PV/T and PV/T/PCM modules are heat pipe applied modules. In our system, 3/8” copper pipe was used in the heat pipe. The pipe installation was performed by selecting the parallel modulation type. The copper pipe was connected to the circulation pump at the module outlet. The output of the circulation pump was connected to the TEG circuit. In PV/T, the heat pipe was fixed to the surface. A 10mm thermal insulation material was applied to the heat pipe to reduce heat loss from external surfaces in the TEG system. Due to the dimensions and small surface area of the TEG system, heat losses were neglected. In PV/T/PCM, the pipe installed was covered with PCM and fixed on the panel surface. TES type (TE) module was preferred in TEGs. As seen in Figure 4, the heat exchanger consists of (841×122×12) mm sized aluminum cooling blocks.

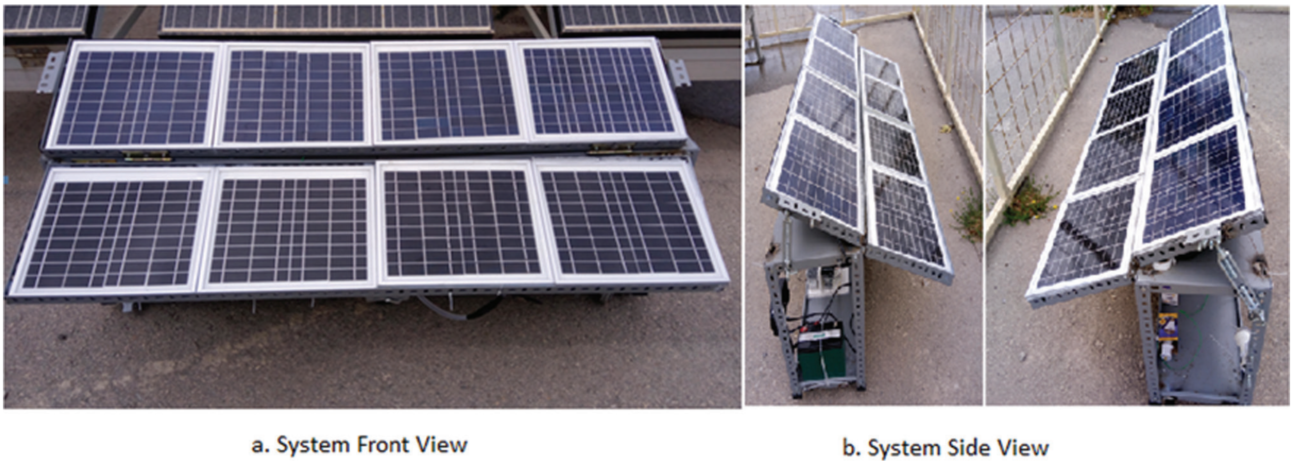

Figure 5. Experimental setup views and module arrays.

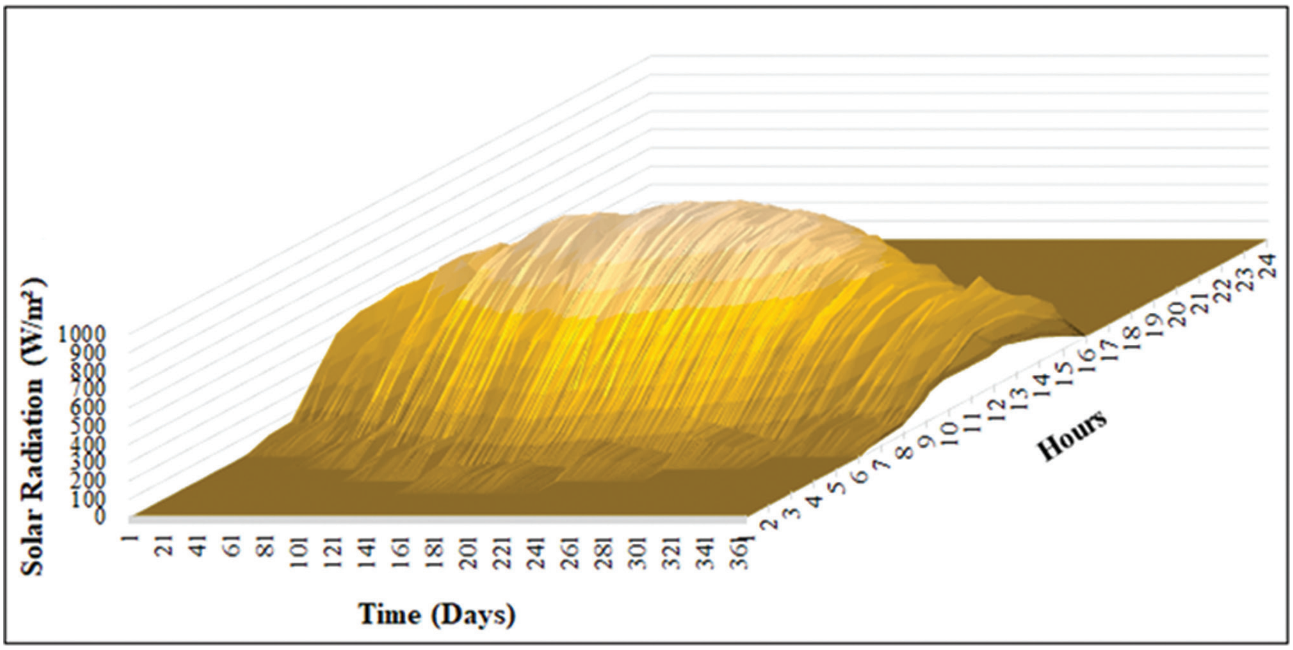

Figure 6. 3D solar radiation data of Kayseri city in 2019.

Waste heat accumulated in modules and capsules is then transferred to water. This source is used to create the hot surface necessary for TEG to generate electricity in the system. TEG, whose surface reaches a high temperature in this way, starts to generate electrical energy by cooling the other surface by means of aluminum finned blocks. In our system, while cooling was applied to one of the aluminum finned blocks, forced cooling was applied to the other.

The front view of the experimental setup is shown as (a) and the side view as (b) (Figure 5). In cases where there is no water circulation in the system, the temperature of the module reaches up to 90°C. The surface temperature of the modules increases over time when using PCM if the circulation is interrupted. Naturally, it takes a long time for the system temperature to decrease. Modules can be adjusted between 0° to 45° in the system. The module angle (38.731) ° was calculated according to the latitude degree of the Kayseri province. When the power is generated in the modules with reference to the year, the panel inclination angle for August is found to be (30-31°). When the power is generated in the modules with reference to the summer months, the module angles are observed to be 16° according to the experimental results given for the month of August.

RESULTS AND DISCUSSION

In this study, the effect of temperature, which is one of the parameters affecting PV module efficiency, was investigated. The suggestions were developed to reduce the effect of temperature, which causes low efficiency in the system. Solar radiation, which is the source of the system, was monitored annually. The EKO-MS-402 Pyranometer was included in the system and solar radiation data was followed. Irradiance data (1 January 2019 - 31 December 2019) were observed for one year. The data received from the system were recorded in minute periods. The data was modeled in 3D by taking the hourly averages of the radiation data (Figure 6).

As seen Figure 6, the radiation values increase in summer and at noon throughout the day. The average daily solar radiation amount is 500 kW/m^2, while the average daylight duration for the summer months reaches up to 12 hours. Radiation values, which reach the maximum level in the summer months, decrease in the winter months.

The changes on the module operating temperature, current, voltage and power output, that happened with adding additional applications on the module surface were observed. It was found that keeping the module temperature values close to the test conditions affects the module efficiency positively. Module temperatures constantly change in proportion to solar radiation (Figure 7). Solar radiation measurement hours vary between 970-1055W/m^2 (Figure 7).

As seen in Figure 7, the surface temperatures of PV, PV/T, PV/T/PCM, PV/PCM modules vary between 33°C and 74°C depending on the amount of radiation. The highest module temperature measured in the experiment belongs to the PV polycrystalline module and is around 73.9°C. The lowest module temperature belongs to the PV/T/PCM (Monocrystalline) module and is around 33.5°C. According to the results, PV/T/PCM monocrystalline and polycrystalline modules are the modules where the ideal surface temperature is observed. Modules close to test conditions should be regarded as ideal modules. PCM and heat pipe applied to monocrystalline and polycrystalline modules were found to be useful for reducing the module temperature. Transient changes in module temperatures were decreased. This situation positively affected the module efficiency. Economic applications to reduce the module temperature should be investigated in the upcoming years.

The voltage values due to solar radiation are also determined in the current study and it is shown in Figure 8.

It is found that module output voltage increases with the increase in solar radiation. The time period when the irradiation value is the highest is the midday. Depending on the amount of radiation, the ambient temperature is observed to be around 37°C between 13:00-13:30 hours. The voltage outputs of PV, PV/T, PV/T/PCM, PV/PCM modules vary between 19 and 20 volts depending on the amount of radiation and module temperature. In our experiment, the highest voltage level was measured as 19.97V from the

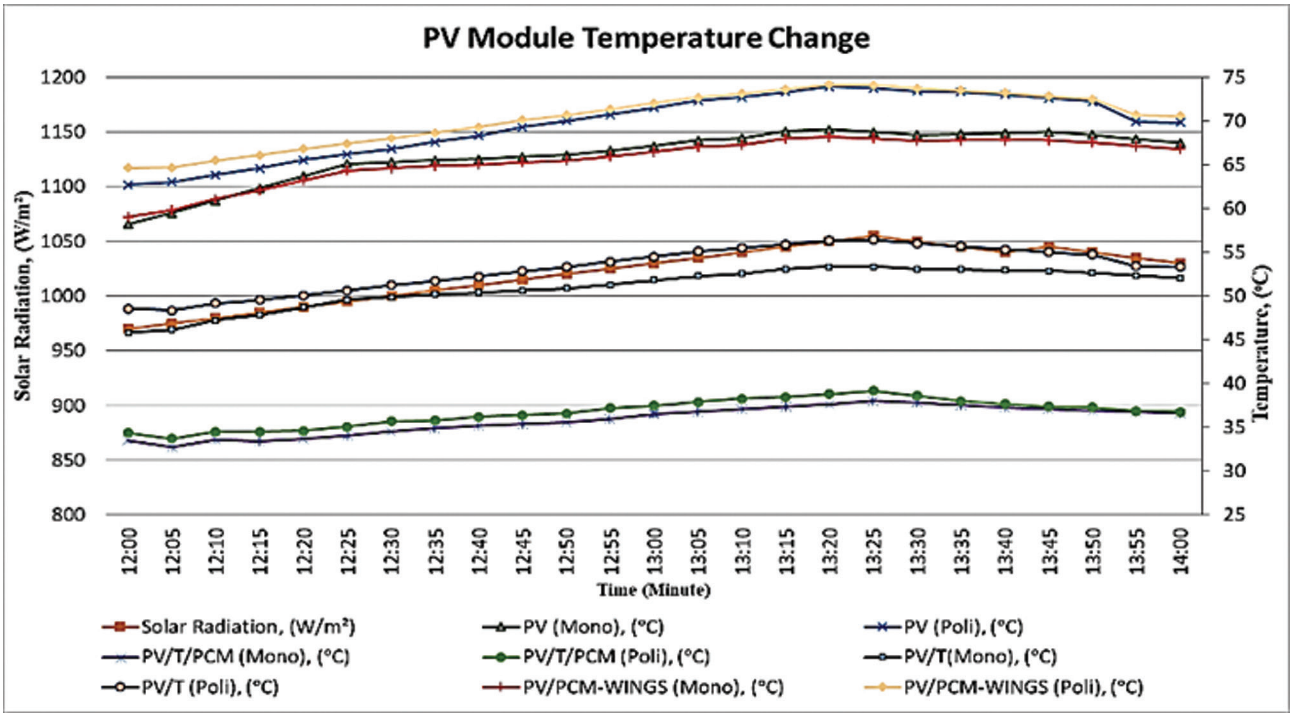

Figure 7. Change in module temperature due to solar radiation (26.08.2019).

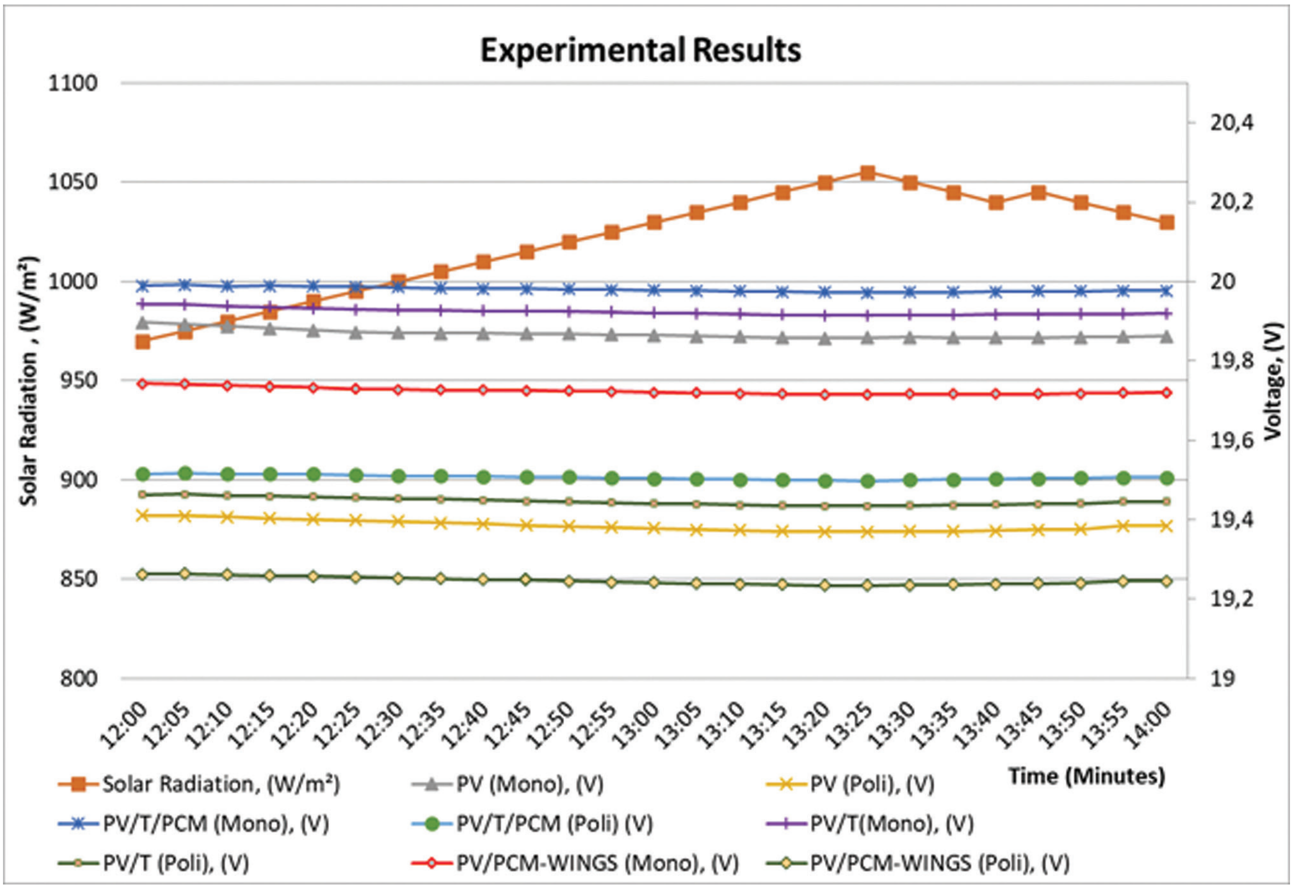

Figure 8. Voltage values due to solar radiation.

PV/T/PCM (Monocrystalline) panel output. The power generation of the modules was between 9.5W and 9.8W on average (Figure 8). While the average charging voltage was 14.2V, the consumption power output varied between 12.6V and 13.6V.

The output voltage, output current and power of the PV module vary increasing on the module surface temperature. (Figure 9).

Meanwhile, module current increases with module temperature. In our system, an increase in module currents was about 1/5-1/10 times the voltage drop. Therefore, the module output power decreased due to the temperature increase (Figure 9). The decrease in solar radiation and ambient temperature lowered the operating temperature of the system components. The operating temperature of the system components remained below 40°C. Therefore, external cooling applications were not applied.

The efficiency of PV modules is directly related to temperature. It is shown graphically in Figure 10.

PV modules are exposed to variable solar radiation, under atmospheric conditions. Module temperatures are constantly changing due to radiation values and environmental influences. Module efficiencies also vary depending on module temperatures. Module efficiency decreases by 10% due to the increase in temperature (Figure 10). Heat pipe and PCM balance the temperature in PV/T/PCM monocrystalline and polycrystalline modules. In PV/T/PCM modules, efficiency loss due to temperature increase is 1%. The module power changes depending on the PV module temperature changes, according to the formula (6). As the module temperature increases, the module power decreases. Depending on this situation, module efficiency decreases.

The efficiency of TEG modules is directly related to the temperature difference. It is shown graphically in Figure 11. Due to the characteristics of semiconductor modules, the power of TEG modules increases as the temperature difference increases. When the temperature difference between the surfaces is 15°C, the naturally cooled TE gives 0.45V energy output, while the forced-cooled TEG gives 0.97V energy output. TEG output power increases up to 5W depending on the temperature difference between surfaces. When TEGs are heated above 150°C, deterioration in the module structure begins.

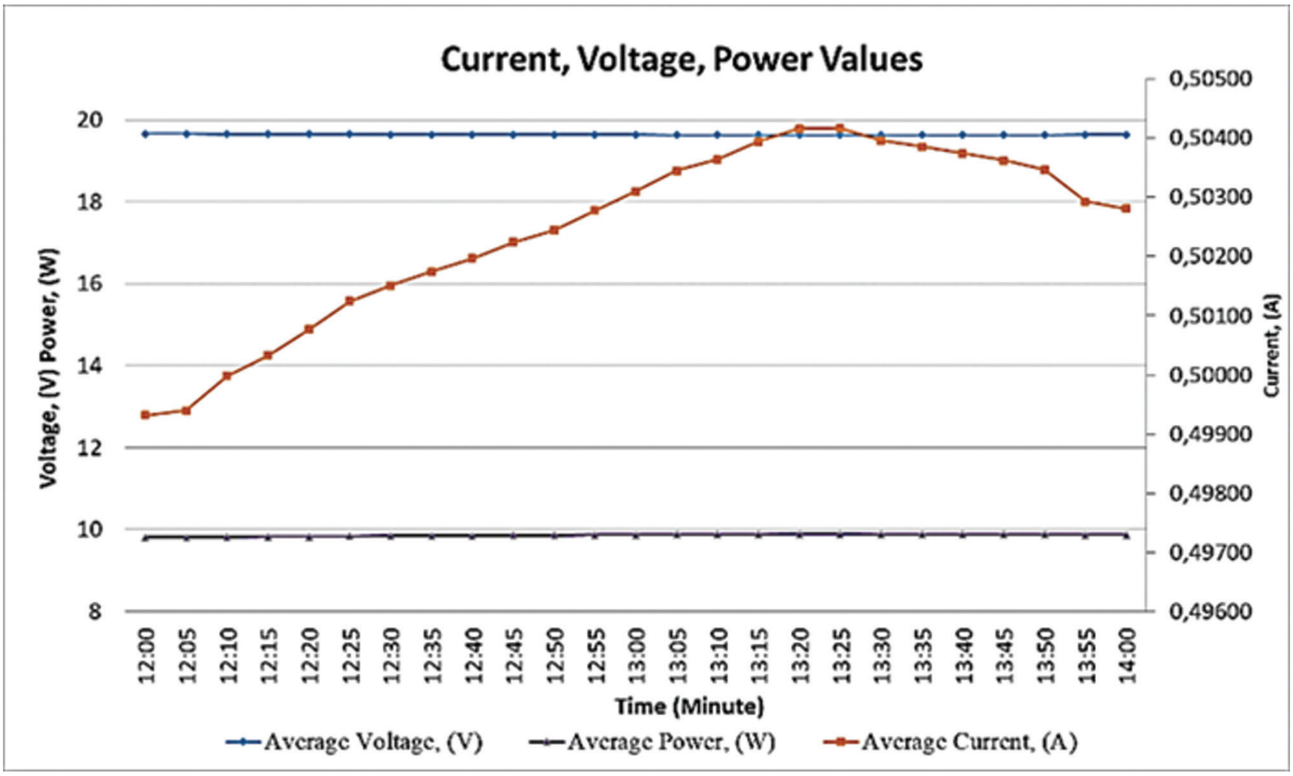

Figure 9. Average current, voltage, and power values in modules.

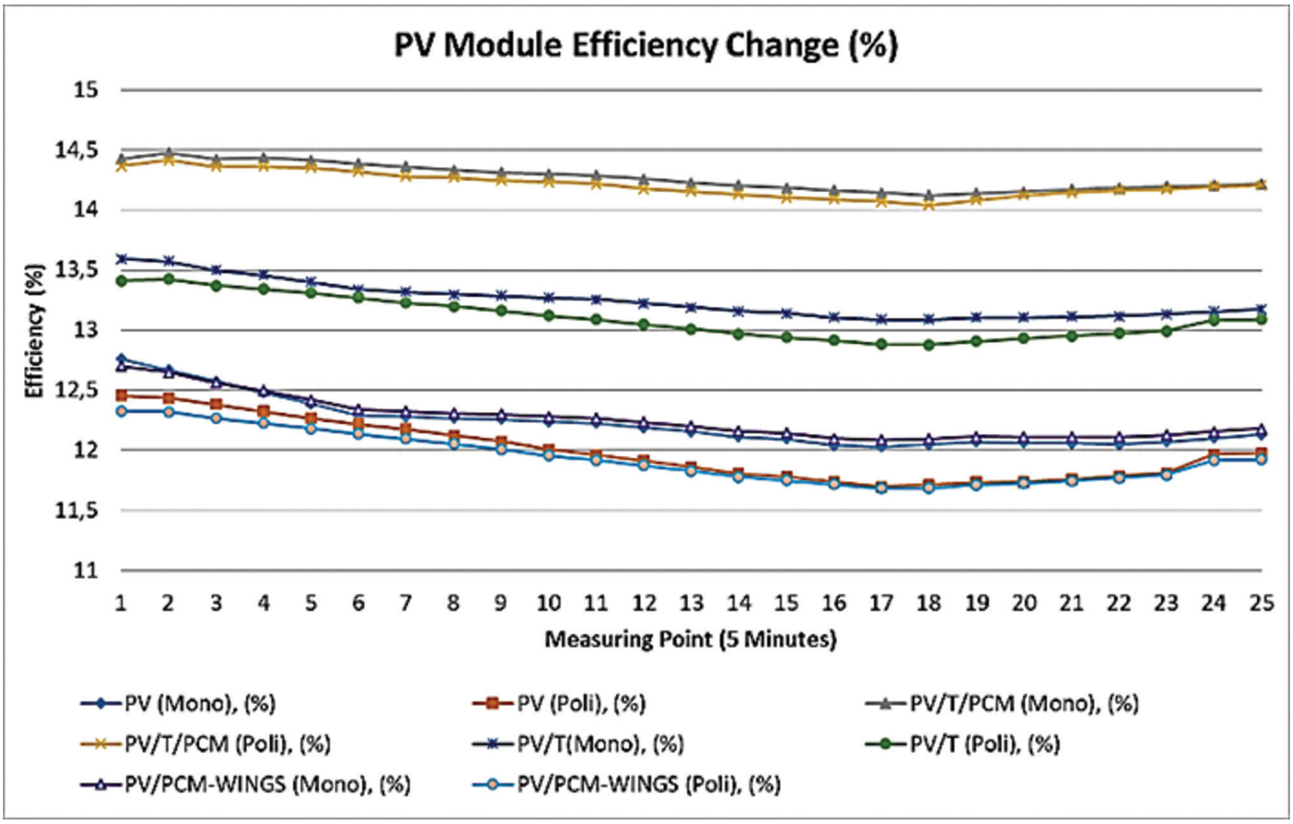

Figure 10. Efficiency changes of PV modules.

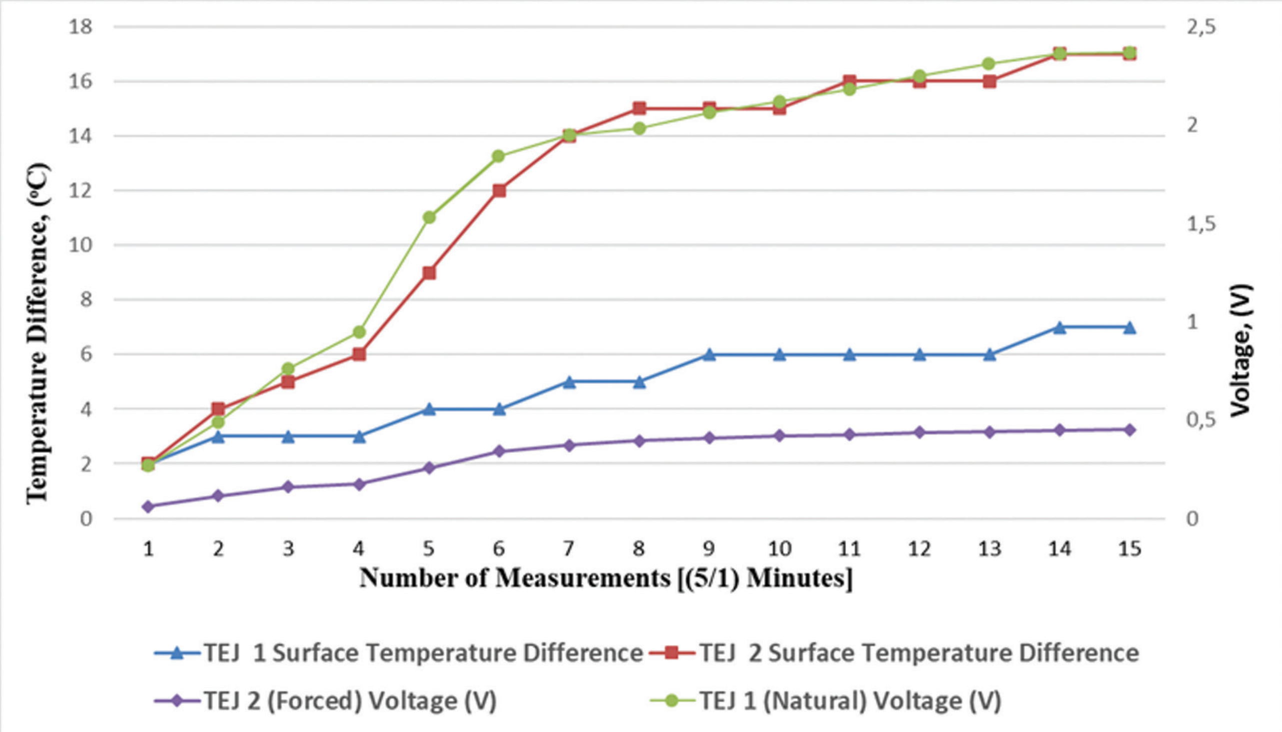

Figure 11. Electricity generation due to temperature difference between TEG's surfaces.

As the module operating temperature increases, the module efficiency begins to decrease. The efficiency increases when the module operating temperature decreases. For this reason, PCM used in PVs should have high thermal conductivity, high latent heat capacity and low cost. To increase the use of PCM in PV modules, the system must be technically and economically feasible. PCMs applied to the system can be used by encapsulation or can be mixed with nanoparticles. It is reported that increasing the thermal conductivity of PCMs, the heat storage capacity and the number of cycles are the solutions that can be suggested for being economical [29]. New methods should be developed in order to reduce the PV module operating temperature. Thus, efficiency loss due to temperature increase will be prevented. It is anticipated that the total energy utilization rate of the PV/T-PCM system can be improved with a reasonable thermal regulation strategy. More work on economic analysis is needed for the system to be economical [30].

The fluid temperature coming from PV/T and PV/T/PCM reaches 50°C. The temperature difference between the surface PCMs affects TEG efficiency (Figure 11). When the fluid temperature increases, the temperature difference between surfaces also increases. As the temperature difference increases, the TEG voltage and current also increase. Natural cooling is performed in TEG 1 and forced cooling in TEG 2. In forced cooling, the heat discharged surface maintains its low temperature due to airflow. For this reason, the voltage value is measured to be higher as compared to natural cooling.

The operating temperature of PV monocrystalline and polycrystalline modules were found to be higher than that of PV/T and PV/T/PCM modules. In conventional modules, the surface temperature can rise to 80°C. Through the water used for cooling the PV/T and PV/T-PCM modules, electricity is produced in the system as a hybrid with TEG. TEG added to the system transforms the waste heat into useful work. TEG can generate power up to 5W depending on the temperature difference. The inlet temperature for TEG 1 and TEG 2 varies between (33-49) °C. When the inlet water temperature rises, the temperature difference between the surfaces of the modules increases. As seen Figure 11, an increase in the temperature difference causes a rise in the output voltage as well. The surface temperature rises believed to be due to the insufficient heat absorption in the natural dissolution system. In the forced system, the temperature rises on the cooling surface stops.

CONCLUSION

Reducing the operating temperature of the modules, as well as the transient temperature fluctuations in the system, are important factors for preventing efficiency loss in photovoltaic modules. Therefore, an experimental study has been carried out with the aim of decreasing the module temperature. The heat accumulated in the PV modules was used to generate electricity with TEGs. The findings are summarized below:

- Use of PCM in PV modules reduces the module operating temperature.
- Temperature of the traditional PV modules is higher than the modules with active and passive cooling. Module temperature, which affects the PV module efficiency, can be controlled by applying PCM to the modules. A decrease in the module temperature directly affects the module efficiency positively.
- Waste heat generated in PV modules is the energy source for TEG. It can work as a PV/TEG hybrid system. In this case, the overall efficiency of the system increases.
- Newly developed PCMs with high heat holding capacity are promising for solar energy applications. Waste heat sources are the source for the TEG system. Due to the low efficiency of TEGs, economically obtainable waste heat sources should be used in TEGs.
- In order to increase the efficiency of TEGs, an economical source with high temperature and a well that will discharge the heat at low temperature is required. For TEG, making the temperature difference with natural cooling will contribute to the economical aspect of the system. If the temperature difference between the surfaces cannot be achieved by natural cooling, forced cooling should be applied. Due to the low efficiency of TEGs, the energy source used should be economical. For this reason, waste heat and alternative energy sources should be preferred in the system. If energy investments are not economical, a system can turn from an advantageous to a disadvantageous state.
- Increasing the thermal conductivity of PCM, choosing the ideal encapsulation method and using ideal surface coating materials will increase the heat transfer. Gaps that will occur on PCM coated surfaces will adversely affect the solar cell temperature. Phase transition temperature, thermal conductivity and latent heat holding capacity of PCMs will affect the system's performance. Therefore, PCM compatible with PV modules should be selected. New PCMs that can be used in PV modules should be developed or PCMs compatible with modules should be investigated. To make the PV module more efficient, solutions to limit the temperature rise should be explored. The hybrid system formed when PV/T and TEG are combined increases the overall performance [31]. The efficiency of the PV module directly depends on the surface temperature of the module. TEG efficiency is proportional to the temperature difference between the surfaces. Therefore, nanofluids can be used as heat carriers in hybrid systems. PV/T module temperature is reduced by 15% when nano liquid is used. PV/T-TEG efficiency increases by 7% [32]. Therefore, nanofluids are an ideal research topic for PV/T-TEG hybrid systems. PCM cooling is best for storing energy in a specific region per unit volume. Finned structure combined with PCM further increases efficiency [33].

Studies in the literature to reduce the temperature of the PV module increase the efficiency. When the PV system is used with TEG and hybrid, the total efficiency increases. There are economic problems with the system. In the studies carried out, economic analysis should be made for the system to work economically and to be easily applicable.

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NOMENCLATURE

α	Average seebeck coefficient
ΔT	Temperature difference between surfaces
R_{in}	TE module average internal resistance
R_L	Load resistance
η	Efficiency
β	Temperature coefficients of solar cells
τ_g	Absorption rate of solar radiation
α_h	Absorption rate of solar radiation
PF	Packaging factor
P_{max}	Maximum power
F	Filling factor
V_{mp}	Maximum voltage
I_{mp}	Maximum current
V_{oc}	Open circuit voltage
I_{sc}	Short circuit current
$\dot{E}_{net}$	Electrical gain from the module
A_m	Module surface area
P_m	Installed power
GS_{ort}	Average annual sunbathing time
η_{inv}	Inverter efficiency
P_{stk}	Module power in standard test conditions
T_h	Cell temperature in working conditions

Abbreviations

PV	Photovoltaic
PV/T	Photovoltaic/Thermal
PV/PCM	Photovoltaic/Phase Change Material
PV/T/PCM	Photovoltaic/Thermal/Phase Change Material
TE	Thermoelectric
TEG	Thermoelectric Generator

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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