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Evaluation of solar panel cooling systems using anodized heat sink equipped with thermoelectric module through the parameters of temperature, power and efficiency

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ABSTRACT

Today, the importance and usefulness of renewable energies is known to everyone. One of the most widely used renewable energies is solar energy. A challenge in the production of electricity from the solar energy is an increase in the surface temperature of solar cells caused by ambient temperature and operating temperature, which reduces the efficiency and performance of solar photovoltaic systems. For every degree increase in ambient temperature, PV panel's efficiency decreases by 0.5%. The system developed in this research consists of two main parts: solar panel and cooling units. The system's performance in two cooling modes of using a thermoelectric module and natural cooling of the system was compared with free convection. The results showed that the use of thermoelectric module with heater could increase the efficiency and power of solar panels by an average of 10.50% and 10.50%, respectively. The temperature of the solar panel during the test time was on average about 10.04 °C lower than normal operating conditions. The results of this study showed that the industrial design of solar panels with a system to reduce excess heat from solar radiation – can be useful and effective in increasing overall efficiency through reducing excess heat and increasing efficiency of the panels.

Introduction

Solar energy is one of the most important sources of renewable energy that is always available and does not produce waste of any particular type [1,2]. Demand for low-cost energy has increased the use of solar systems to generate electricity through solar radiation. However, the efficiency, productivity and longevity of solar panels are significantly affected by climatic conditions such as ambient temperature and operating temperature [3,4,5]. It has been reported that only about 15 to 20% of the solar radiation absorbed by a solar panel can be converted into electricity and the rest is wasted as heat [6,7,8].

In a study, Ding et al. investigated the possibility of generating electricity using thermoelectric modules by extracting heat from a solar pool. The results of the study showed that in ideal conditions, such a system costs at least 10 times more compared to other renewable energy sources such as off grid solar systems with storage equipment [9]. In another study, Gharzi et al. examined different methods of cooling photovoltaic solar modules. They reported that proper cooling of solar systems improves their electrical, thermal and overall efficiency, which in turn reduces cell degradation and maximizes the life of solar panels [10]. Rajaee et al. conducted an experimental analysis of a solar panel using cobalt nanofluid and phase-shifting materials. Their results showed that the use of cobalt nanofluid increased the overall efficiency by 12.28% compared to the use of water as a coolant. Also, using both the phase-shifting method and the application of a 1% concentration of nanofluid increased the overall efficiency of the system by 4.52% [11]. Liu et al. examined the use of solar thermoelectric cooling technologies for zero-energy buildings. They reported that the coefficient of performance in a solar thermal air conditioning system and a solar thermal energy storage air conditioning system could reach 1.90 and 1.22, respectively, both of which are more efficient than a conventional thermal cooling system with an average coefficient of 0.3–0.4 [12]. Riffat and Ma, studied thermoelectric potential measurement and reviewed its current applications. They reported that thermoelectric modules are reliable energy converters. One of the most important advantages of using them is the absence of noise or vibration due to the

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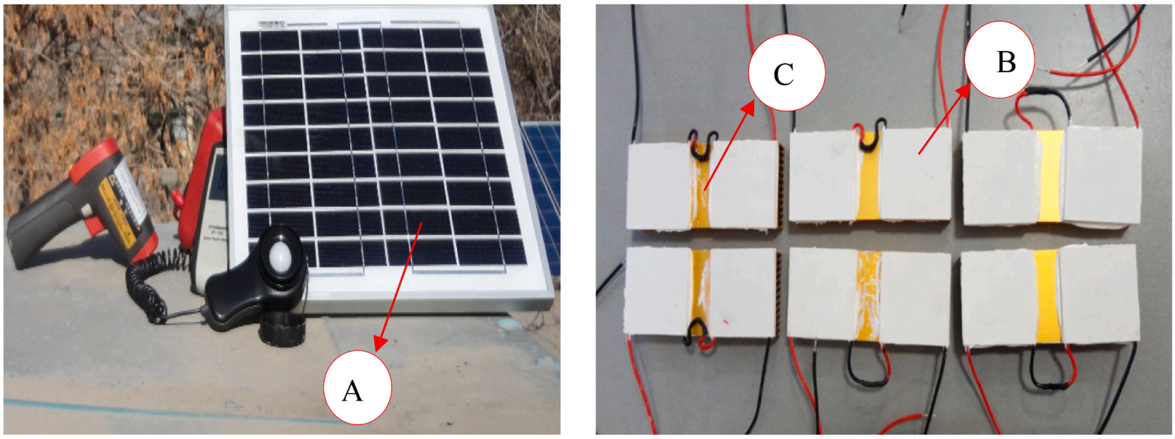


Fig. 1. The system presented in this study: A) Solar panel, B) Thermoelectric module, C) Heat sink.

Table 1
Technical specifications of the thermoelectric module.

Temperature difference	Voltage and output current
20°	open circuit voltage equal to 0.97 V and short circuit current of 225 mA
40°	open circuit voltage equal to 1.8 V and short circuit current of 368 mA
60°	open circuit voltage equal to 2.4 V and short circuit current of 469 mA
80°	open circuit voltage equal to 3.6 V and short circuit current of 558 mA
100°	open circuit voltage equal to 4.8 V and short circuit current of 669 mA

absence of any moving mechanical parts and also their very small size and weight. For this reason, their use has expanded to a wide range of applications [13]. Kane and Verma, increased the performance of solar panels using thermoelectric coolers. They first studied the theory of systems and then optimized the system with thermoelectric modules. Their results showed that improvement in a BIPV module's performance and life can be achieved by cooling to the system to 10 °C [14]. He et al. investigated the combination of thermoelectric modules with a solar collector using heat pipe discharge. In their research, they theoretically and experimentally analyzed the cooling and heating systems of a thermoelectric that worked with solar energy. Their results showed that when water temperature increases from 25 °C to 55 °C, electrical efficiency decreases from 1.625% to 1.255%, while the thermal efficiency decreases from 59.36% to 52.96% [15]. Therefore, considering the importance of the above-mentioned issues and the necessity of reducing the operating temperature of solar panels, this study is aimed at providing a solution to cool solar panels and reduce the heat generated from their surface of in order to increase the efficiency and life of solar panels using an anodized heat sink equipped with a thermoelectric module.

Materials and methods

Designed system and equipment

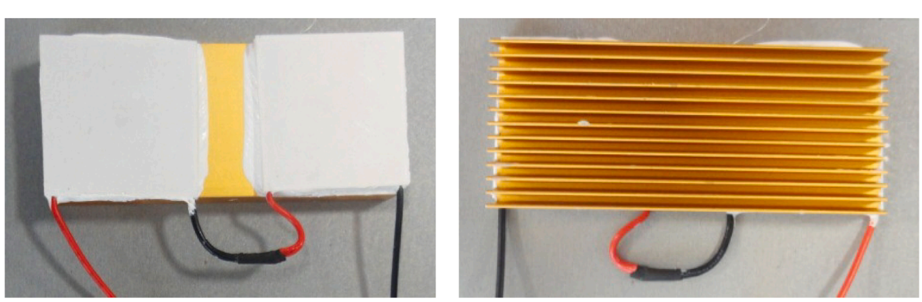
In this study, a laboratory system for cooling solar panels was constructed using a heat sink equipped with a thermoelectric module (Fig. 1).

Preparation of the thermoelectric module with heat sink

First, six thermoelectric modules model SP1848 with dimensions of 4×40×40 mm and weight of 25 g were prepared. Then, an anodized aluminum heat sink with dimensions of 10×40×100 mm was prepared. The heat sink was mounted on the module for better cooling of the thermoelectric module. In order to connect the thermoelectric module to the solar panel, improve the heat transfer coefficient and to connect the heat sink with the thermoelectric module, a 45 g Kafuter K704 silicone adhesive was used. The hot part of the thermoelectric module was connected to the back of the solar panel and the cold part of it was connected to the heat sink. The outputs of the thermoelectric modules were connected in series. The technical specifications of the thermoelectric module are given in Table 1 and the actual view of the thermoelectric module with the heat sink is shown in Fig. 2.

Equipment used

A solar power meter was used to measure the amount of radiant power. A multimeter was also applied to measure the amount of current and voltage. To measure the ambient temperature and the surface temperature of the solar panel, a laser thermometer was used (Table 2).



(A) **(B)**

Fig. 2. A) Thermoelectric module, B) Anodized heat sink.

Table 2
Technical specifications of the equipment used in this study.

Equipment	Model	Made in	Precision	Description
Solar panel	Yingli	China	10 V	280×358×18
Multimeter	UT-136C	Canada	0.1 V	Measuring AC voltage up to 400 V, DC voltage up to 500 V and AC direct current up to 10A
Solar power meter	ST-1307	Iran	±10 W/m^2	Measurement range of 1999 W/m^2
Laser thermometer	UT-301A	Canada	±18	Temperature measurement range of −18 to 350 °C

Table 3
Descriptive indicators for the variables under study in two solar panels.

Variable	Type of Solar Panel	Number	Mean	Standard Deviation	Coefficient of Skewness	Coefficient of Kurtosis	Minimum	Maximum
Solar panel temperature	Standard solar panel	21	36.61	5.90	−3.47	13.60	13.10	39.51
	Solar panel with thermoelectric module	21	27.00	4.17	−2.54	7.73	12.10	29.79
Ambient temperature	Standard solar panel	21	14.50	2.41	−0.72	−1.12	10.11	17.68
	Solar panel with thermoelectric module	21	14.50	2.41	−0.72	−1.12	10.11	17.68
Power	Standard solar panel	21	11.62	0.58	1.53	4.38	10.73	13.49
	Solar panel with thermoelectric module	21	12.85	0.64	1.30	3.58	11.83	14.82
Variations in efficiency	Standard solar panel	21	0.12	0.01	3.42	13.71	0.11	0.16
	Solar panel with thermoelectric module	21	0.13	0.01	3.47	14.05	0.12	0.17

Experiments

When solar panels are launched, they heat up after a short time as a result of the sunlight and their operation, and this heat reduces the efficiency of the solar panels. The heat of the panel is transferred to the thermoelectric module that is behind the heat sink. The heat sink is connected to the head of the thermoelectric module to be cooled through free convection (free air flow). Therefore, due to the temperature difference between the two module plates, a potential difference occurs, an electric current and voltage are generated and the solar panel is cooled. The experiments of this study were performed on a sunny day in winter under temperature conditions at a 45-degree angle from a (10 W) solar panel (Fig. 2). The temperature of six points on the surface of the solar panel, behind which the thermoelectric modules were installed, was recorded simultaneously using a thermometer and the maximum value was recorded. All experiments were performed at variable ambient temperatures between 10 and 17 °C. The recorded variables were maximum power (P_{max}), maximum voltage (V_{max}) and maximum current (I_{max}) generated during the experiment. The experiments were conducted between 9:00 AM and 2:00 PM. Data were recorded every 15 min with three replications to ensure the accuracy of the experiment and reduce human error.

Criteria for the evaluation of the proposed system

In order to compare the output power and efficiency of the system under normal operating conditions and in the thermoelectric module application mode, Eqs. (1 and 2) were used [16]. Equation (1) was applied to calculate the output power. The definition of efficiency in solar cells should be used to compare the results for different cell exposure times to different solar radiation levels. The definition of efficiency is given in Equation (2).

$$P = I \times V \quad (1)$$

$$\eta = \frac{P}{Ir(t)A} \quad (2)$$

where I_r is the amount of solar radiation in $(\frac{W}{M^2})$ and P is the output power of the panel in (W). A is the area of the solar panel in (m^2).

Statistical analysis

Statistical analysis of the results was performed using the means comparison test. To compare the system under normal operating conditions and while the thermoelectric module was applied; *t*-test was used at a 1% significance level.

Table 4
Descriptive indicators for the variables under study in two solar panels after the exclusion of the outlier data.

Variable	Type of Solar Panel	Number	Mean	Standard Deviation	Coefficient of Skewness	Coefficient of Kurtosis	Minimum	Maximum
Solar panel temperature	Standard solar panel	20	37.78	2.46	−1.23	−0.28	32.90	39.51
	Solar panel with thermoelectric module	20	27.74	2.45	−1.15	−0.50	23.11	29.79
Ambient temperature	Standard solar panel	20	14.71	2.24	−0.83	−0.88	10.50	17.68
	Solar panel with thermoelectric module	20	14.71	2.24	−0.83	−0.88	10.50	17.68
Power	Standard solar panel	20	11.53	0.41	−0.03	−0.02	10.73	12.32
	Solar panel with thermoelectric module	20	12.75	0.46	−0.13	−0.05	11.83	13.59
Variations in efficiency	Standard solar panel	20	0.18	0.004	0.46	−0.18	0.11	0.12
	Solar panel with thermoelectric module	20	0.13	0.004	0.33	0.003	0.12	0.13

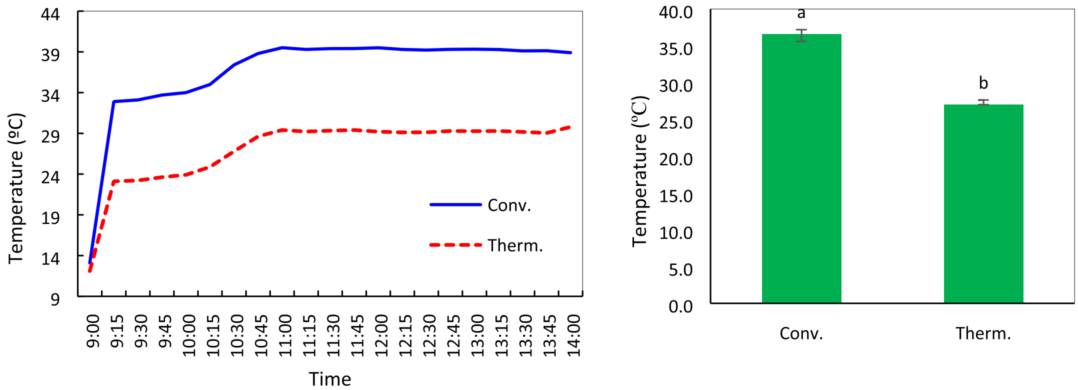


Fig. 3. Comparing surface temperature variations of the solar panel under normal operating conditions and when a thermoelectric module is used.

Results and discussion

The results of the present study consist of changes in temperature, output power and efficiency of a solar panel under normal operating conditions compared with changes in the same variables when a cooling system equipped with a thermoelectric module is used in the solar panel. Research variables were identified through descriptive indicators before reviewing and comparing the results. Table 3 presents the values for the mean, standard deviation, coefficient of skewness and coefficient of kurtosis as well as the minimum and maximum values of each variable for the two solar panels studied.

The skewness and kurtosis observed for the variables indicates that both the distribution of the ambient temperature and power are normal but the solar panel temperature and efficiency variations do not have normal distribution. The first set of data was recorded at 9 am. Compared to the other sets of data recorded, this set of data was outlier data, so it was excluded from further analysis. The results to be included for analysis after the removal of the outlier data are given Table 4.

The skewness and kurtosis values for the variables show that after deleting the first set of data recorded on both panels, the distribution of all the research variables is normal.

Results of evaluating the use of thermoelectric module on reducing solar panel temperature

Solar panel surface temperature variations using the thermoelectric module and without it during the test time are reported in Fig. 3. The temperature of the solar panels is a function of ambient temperature and the intensity of solar radiation. The results show that as the ambient temperature increases, the cell temperature also increases. In addition, increase in the intensity of solar radiation, makes the cell heat up and increases its temperature. As can be seen, the temperature of the solar panel in normal operating conditions is on average 37.78 °C and the temperature of the solar panel with the electric module is 27.74 °C. The temperature varies in the range of 32.9% to 39.51% for the solar panel in normal operating conditions and between 23.11% and 29.79% for the panel with the thermoelectric module. The results showed that on average, the use of the thermoelectric module could keep the temperature of the solar panel about 10.04 °C lower than normal operating conditions. In other words, considering the average temperature of the solar panel, it can be concluded that a 26.5% decrease in panel temperature has occurred using the thermoelectric module. Also, the result of comparing the means for the two modes of normal operating conditions and the use of the thermoelectric module was significant at the level of 1% probability.

Lin et al. studied thermal management of high-power LEDs based on thermoelectric cooling and micro-channel with nanofluid cooling. Their results showed that the use of nanofluids instead of water as a cooling fluid can reduce the temperature to 18.5 °C [17]. Wongwuttanasatian et al. evaluated increase in the performance of a solar panel with passive cooling using phase change materials in a source equipped with a heat sink. The results of their research showed that the use of phase change materials in a source equipped with a heat sink can reduce the temperature of the solar panel by about 6 °C and lead to an increase in efficiency of about 5.3% [18]. Ruth and Walke, examined the cooling of the air inside a car using a thermoelectric module. In their research, six thermoelectric modules were used to cool the car air with DC power supply. The results showed that the use of that system could reduce the air temperature inside the cabin from 32 °C to 25.8 °C [19]. To improve temperature conditions and increase the efficiency of solar panels, Nada et al. used a hybrid system that consisted of aluminum nanoparticles and phase change materials. The results of their research showed that the integration of those two materials into the back of the solar panel reduced panel temperature for 8.1 °C to 10.6 °C and increased panel efficiency by about 5.7% to 13.2% [20]. The results showed that the use of thermoelectric module was effective in absorbing excess heat in solar panels and directing it to the ambient by the heat sink, which results in optimal panel operation and increases the lifespan of solar panels due to optimal operating conditions.

According to the results, correlations between ambient temperature and cell temperature for normal operating conditions and the use of the thermoelectric module were 0.958 and 0.964, respectively. Due to the normality of cell temperature in both panels, *t*-test can be used to compare the average cell temperature in the two panels (Table 5).

The results of the *t*-test show that the average temperature of the solar panel with a thermoelectric module is significantly lower than that of the normal solar panel.

Table 5
Results of comparing the average temperature in the two solar panels through *t*-test.

Variable	Solar panel	Number	Mean	Standard deviation	Leven's test		test statistic	*t*-test	
					Test statistic	p-value		Degrees of freedom	p-value
Solar panel temperature	Normal	20	37.78	2.46	0.007	0.93	12.90	38	0.00
	with thermoelectric module	20	27.74	2.45					

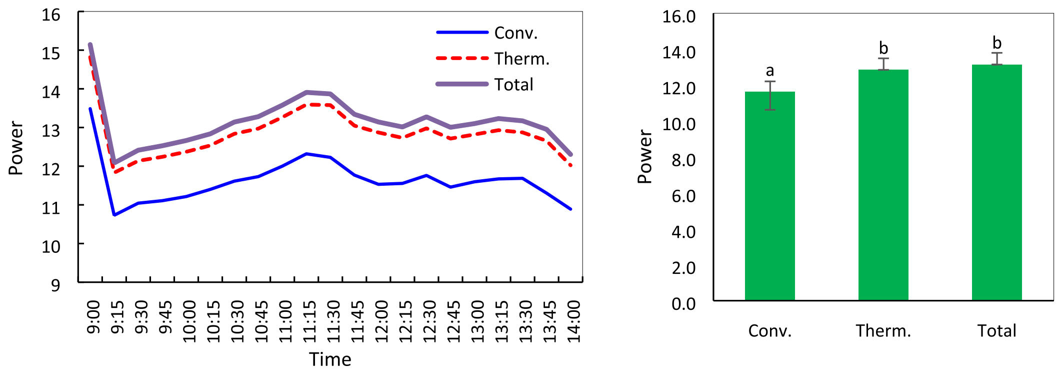


Fig. 4. Variations in the output power of the solar panel under normal operating conditions and the one using a thermoelectric module.

Table 6
Comparing the average power in two solar panels with *t*-test.

Variable	Solar panel	Number	Mean	Standard deviation	Leven's test		test statistic	*t*-test	
					Test statistic	p-value		Degrees of freedom	p-value
Solar panel temperature	Normal	20	11.53	0.41	0.22	0.63	−8.79	38	0.00
	with thermoelectric module	20	12.75	0.46					

Effects of using a thermoelectric module on the output power of the solar panel

Fig. 4 shows variations in the output power of the solar panel using the thermoelectric module and the one without it during the test time. The average power of the solar panel in normal operating conditions is 11.53 W and for the solar panel with a thermoelectric module, it is 12.75 W, which shows a 10.5% increase in the power of the panel with a thermoelectric module. The range of power changes in the solar panel with normal operating conditions varied between 10.73 and 13.49 W and for the solar panel using the thermoelectric module, it fluctuated in the range of 11.83–14.82 W. The maximum amount of power was obtained in the solar panel with normal operating conditions and the panel with thermoelectric module was 12.32 and 13.59 W, respectively. The highest output power observed in the thermoelectric module installed behind the solar panel during the test was 0.33 W. Fig. 4 shows the power values as well as the total power obtained from the solar panel on which the thermoelectric modules were installed. Difference in the means of the panel with normal operating conditions and the one with the thermoelectric module was significant at the 1% probability level.

Sheyda et al. studied the application of a two-phase current for cooling solar panels in combination with microchannels. The results of their research showed that the use of the technique compared to normal operating conditions could increase the maximum output power of the solar panel by 38% [21]. Tundee et al. generated electricity from a solar pool using a combination of the thermosyphon phenomenon and thermoelectric modules. Their results showed that the use of thermoelectric modules in solar pools could generate 234.25 mV of power [22]. Shittu et al. performed a mechanical and electrical analysis of a solar thermoelectric module under split heat flux. They subjected a thermoelectric module to four different split heat fluxes. Their results showed that in the optimal state, the output power increased by 59.12% compared to the sample without heat flux split [23]. Bamroongkhan et al. assessed the energy conversion efficiency of a new hybrid solar system that used photovoltaics, thermoelectrics and heat. Their results showed that using a fan in the system for cooling, increased the output power by about 21.42% compared to normal operating conditions [24]. Yang and Yin examined the energy conversion efficiency of a new hybrid solar system using photovoltaics, thermoelectrics and heat. They designed a hybrid solar system that consisted of thermoelectric and photovoltaic modules and water pipes to cool the system. They reported an increase in production capacity of up to 30% [25]. According to the results of their research, it can be stated that a thermoelectric module can lead to the optimization of energy consumption and prevent energy loss in solar

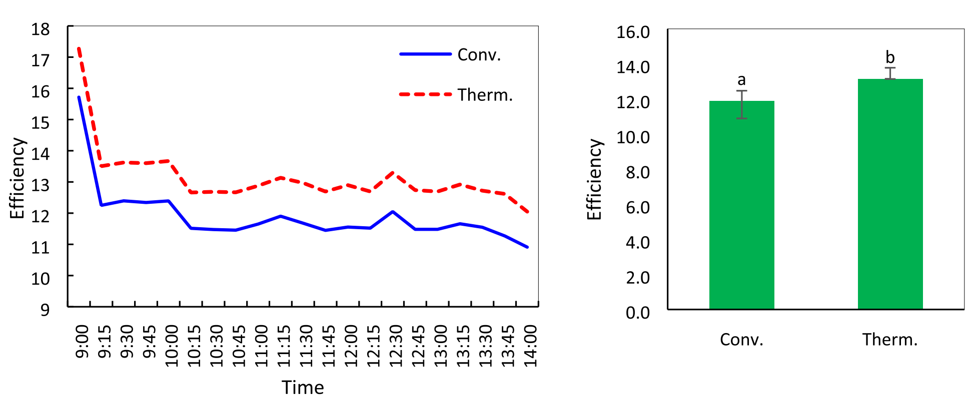


Fig. 5. Comparison of changes in solar panel surface efficiency under normal operating conditions and when using a thermoelectric module.

Table 7
Comparison of mean efficiency changes in two solar panels with *t* test.

Variable	Solar panel	Number	Mean	Standard deviation	Leven's test		test statistic	*t*-test	
					Test statistic	p-value		Degrees of freedom	p-value
Solar panel temperature	Normal	20	0.11	0.004	0.22	0.83	−9.56	38	0.00
	with thermoelectric module	20	0.13	0.004					

panels.

Due to the normality of power distribution in both panels, *t*-test can be used to compare power in the planes. The results of *t*-test comparisons are presented in Table 6. The results of *t*-test show that the average power of the solar panel with a thermoelectric module is significantly higher than that of a normal solar panel.

Evaluating the effect of using a thermoelectric module on the efficiency of the solar panel

Variations in solar panel efficiency using a thermoelectric module and without it during the test time are reported in Fig. 5. The efficiency of solar panels is the ratio of output power to input power. The results show that the use of thermoelectric module can increase the efficiency of solar panels by an average of 10.50%. The average efficiency change on a normal solar panel was 0.117% and on a panel with a thermoelectric module, it was 0.129%, indicating a 10.5% improvement. Difference in the means of the normal operating panel and the panel with a thermoelectric module is significant at the level of 1% probability.

In a similar study, Rodrigo et al. investigated the economic and functional limitations of thermoelectric modules on solar systems. In their results, they predicted a maximum efficiency of 39.2% for passive cooling systems [26]. In their paper, Al-Nimr et al. examined a new hybrid solar injection cooling system using a thermoelectric module. They reported that the use of a thermoelectric system to generate electricity for circulating pumps improves system performance by 13.3% [27]. Chandel and Agarwal studied the solar panel cooling technique to increase efficiency through phase-shifting materials. They observed a 5% increase in electrical efficiency with integrated PV-PCM systems. Considering the economic conditions, they reported that due to low thermal conductivity, lack of performance increase over time and high system costs, the use of phase change materials cannot be a desirable economic solution [28]. Therefore, no need for additional pumps and circulating systems and thus no problems related to service and maintenance are among the advantages of the system used in their research since they used a water circulation system to cool the solar panel.

Due to the normal distribution of efficiency variations on both panels, *t*-test can be used to compare the changes in efficiency on the panels. The results are reported in Table 7. The results of the *t*-test show that the average change in the efficiency of the solar panel with a thermoelectric module is significantly higher than that of a normal solar panel.

Conclusion

The present study was conducted to investigate the relationship between decreasing the temperature of the solar panel and changes in its the power and efficiency in panels with normal operating conditions and the ones equipped with thermoelectric modules. Based on the results obtained, the use of a thermoelectric module and the heat sink technique leads to reduction in the temperature of the solar panel, increasing its the efficiency and output power. The results showed that the cooling system efficiency was optimal. In the best case, the thermoelectric module for heat transfer could increase the efficiency of the solar panels by 10.50% and the output power by 10.50%. During the test time, the observed temperature of the solar panel was on average 10.04 °C lower than that of a panel working under normal operating conditions. Therefore, this study concludes that the thermoelectric module has a positive effect on reducing the temperature of a solar panel and increasing electrical efficiency as a result of cooling the system.

CRediT authorship contribution statement

Rouhollah Salehi: Methodology, Supervision, Data curation, Investigation, Software, Writing – original draft. **Ahmad Jahanbakhshi:** Conceptualization, Methodology, Investigation, Validation, Writing – original draft, Writing – review & editing. **Mahmood Reza Golzarian:** Methodology, Investigation, Validation, Writing – review & editing. **Mehdi Khojastehpour:** Methodology, Investigation, Validation, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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