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
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 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).

Table 1
Technical specifications of the thermoelectric module.

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

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

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 10 A |
| Solar power meter          | ST-1307     | Iran    | ±10 W/m²              | Measurement range of 1999 W/m²                         |
| Laser thermometer          | UT-301A     | Canada  | ±0.18                 | 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 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 |

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).

\[ P = I \times V \]  
\[ \eta = \frac{P}{I(t)A} \]  

where \( I(t) \) 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.
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 | p-value | test statistic | t-test 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  | 20     | 27.74  | 2.45               |                            |         |                |                          |         |
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.

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.

Shayda 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
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 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 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 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**

Rouollah Salehi: Methodology, Supervision, Data curation, Investigation, Software, Writing – original draft. Ahmad Jahanbakhshi: Conceptualization, Methodology, Investigation, Validation, Writing – original draft, Writing – review & editing. Mahmoud Reza Golzarian: Methodology, Investigation, Validation, Writing – review & editing. Mehdi Khajestehpour: 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.

**References**

[1] Tesio, U., Guelpa, E., Verda, V. 2020. Integration of thermochemical energy storage in concentrated solar power. Part 1: Energy and economic analysis/optimization. Energy Conversion and Management: X. 6. 100039.

[2] Kaveh M, Karami H, Jahankhani A. Investigation of mass transfer, thermodynamics, and greenhouse gases properties in pennyroryd drying. J Food Process Eng 2020;43(8). https://doi.org/10.1111/jfpe.v43.810.1111/jfpe.13446.

[3] Popovici CG, Huditeanu SV, Mateescu TD, Cherechea N-C. Efficiency improvement of photovoltaic panels by using air cooled heat sinks. Energy Procedia 2016;85: 425–32.

[4] Alghool DM, Elmekkawy TY, Haouari M, Eloni A. Optimization of design and operation of solar assisted district cooling systems. Energy Conversion and Management: X. 2020;6:100028.

[5] Mata-Torres C, Palenzuela P, Alarcón-Padilla DC, Zurita A, Cardemil JM. Escobar RA. Multi-objective optimization of a Concentrating Solar Power + Photovoltaic + Multi-Energy Distillation plant: Understanding the impact of the solar irradiation and the plant location. Energy Convers Manage 2021;X:100088.

[6] Emam M, Ookawara S, Ahmed M. Performance study and analysis of an inclined concentrated photovoltaic/thermal concentration system. Sol Energy 2017;150: 220-45.

[7] Cioccolanti L, Tascioni R, Pirro M, Artzecni A. Development of a hardware-in-the-loop simulator for small-scale concentrated solar combined heat and power system. Energy Conversion and Management: X. 2020;8:100056.

[8] Dos Santos SAA, Torres JPN, Fernandes CA, Lameirinhas RAM. The impact of aging of solar cells on the performance of photovoltaic panels. Energy Conversion and Management: X. 2021;10:100082.

[9] Ding LC, Akbarzadeh A, Singh B, Remeli MF. Feasibility of electrical power generation using thermoelectric modules via solar pond heat extraction. Energy Convers Manage 2017;135:74-83.

[10] Gharizi, M., Kermani, A. M., Gholaee, Z. & Pakchi, M. (2019). Investigating Different Methods Of Cooling Photovoltaic Solar Modules. International Conference on Renewable Energy and Distributed Generation, Shahid Beheshti University, Tehran, Iran.

[11] Rajaei F, Rad MAV, Kasearian A, Mahian O, Yan W-M. Experimental analysis of a photovoltaic/thermoelectric generator using cobalt oxide nanofluid and phase change material heat sink. Energy Convers Manage 2020;212:112780. https://doi.org/10.1016/j.enconman.2020.112780.

[12] Liu Zhongbing, Zhang L, Gong GuangCai, Li HangXin, Tang GuangFa. Review of solar thermoelectric cooling technologies for use in zero energy buildings. Energy Build 2015;102:207–16.

[13] Riffat SB, Ma X. Thermoelectrics: a review of present and potential applications. Appl Therm Eng 2003;23(8):913–35.

[14] Kane A, Verma V. Performance enhancement of building integrated photovoltaic module using thermoelectric cooling. International Journal of Renewable Energy Research 2013;3(2):320–4.

[15] He W, Su Y, Wang YQ, Riffat SB, Ji J. A study on incorporation of thermoelectric modules with evacuated-tube heat-pipe solar collectors. Renewable Energy 2012; 37(1):142–9.
[16] Mousavi, S., & Sadrameli, S. M. (2016). Design and setup of a cooling system using phase change materials (PCMs) for the efficiency enhancement of solar panels. Mechanical Engineering Sharif, (32:3), 77-92.

[17] Lin Xiaohui, Mo Songping, Mo Bingzhong, Jia Lisi, Chen Ying, Cheng Zhengdong. Thermal management of high-power LED based on thermoelectric cooler and nanofluid-cooled microchannel heat sink. Appl Therm Eng 2020;172:115165. https://doi.org/10.1016/j.applthermaleng.2020.115165.

[18] Wongwuttanasatian T, Sarkarini T, Sukari A. Performance enhancement of a photovoltaic module by passive cooling using phase change material in a finned container heat sink. Solar Energy 2020;195:67-73.

[19] Raut MS, Walke PV. Thermoelectric air cooling for cars. International Journal of Engineering Science and Technology 2012;4(5):2381-94.

[20] Nada SA, El-Nagar DH, Hussein HMS. Improving the thermal regulation and efficiency enhancement of PCM-Integrated PV modules using nano particles. Energy Convers Manage 2018;166:735–43.

[21] Valeh-e-Sheyda Peyvand, Rahimi Masoud, Karimi Ebrahim, Asadi Masomeh. Application of two-phase flow for cooling of hybrid microchannel PV cells: A comparative study. Energy Convers Manage 2013;69:122–30.

[22] Tundee Sura, Sthiamongkolpradit Suparerk. Electric power generation from solar pond using combination of thermosyphon and thermoelectric modules. Energy Procedia 2014;48:453-63.

[23] Shittu Samson, Li Guiqiang, Xuan Qindong, Zhao Xudong, Ma Xiaoli, Cui Yu. Electrical and mechanical analysis of a segmented solar thermoelectric generator under non-uniform heat flux. Energy 2020;190:117433. https://doi.org/10.1016/j.energy.2020.117433.

[24] Bamrongkkhan P, Lertsatitthanakorn C, Soponromnarit S. Experimental performance study of a solar parabolic dish photovoltaic-thermoelectric generator. Energy Procedia 2019;158:528–33.

[25] Yang Dajiang, Yin Huiming. Energy Conversion Efficiency of a Novel Hybrid Solar System for Photovoltaic, Thermoelectric, and Heat Utilization. IEEE Trans Energy Convers 2011;26(2):662-70.

[26] Rodrigo PM, Valera A, Fernández EF, Almonacid FM. Performance and economic limits of passively cooled hybrid thermoelectric generator-concentrator photovoltaic modules. Appl Energy 2019;238:1150–62.

[27] Al-Nimr Moh’d Ahmad, Tahitiouh Boufah, Hasan Albas. A novel hybrid solar ejector cooling system with thermoelectric generators. Energy 2020;198:117318. https://doi.org/10.1016/j.energy.2020.117318.

[28] Chandel SS, Agarwal Tanya. Review of cooling techniques using phase change materials for enhancing efficiency of photovoltaic power systems. Renew Sustain Energy Rev 2017;73:1342-51.