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Research Paper

Thermodynamic and Environmental Assessment of Mounting Fin at the Back Surface of Photovoltaic Panels

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Abstract. Nowadays, researches on different kinds of renewable energies including photovoltaic technology are developing rapidly. It is proved that the output power of a PV cell is reduced by increasing the temperature. In this paper, mounting aluminum fins at the back surface of the PV module is proposed as a simple and low-cost method to decrease the PV cell temperature. It was found that using aluminum fins caused more than 7°C reduction in the cell temperature. Besides, it was shown that the entropy generation of the PV module with fin, was 3.5% lower than the conventional one. Also, the positive environmental impacts of using fins at the back surface of the PV module were estimated by RETScreen software, so that, it leads to enhance the performance of the PV power plant by more than 25 %, from an environmental viewpoint.

Keywords: Photovoltaic, Entropy, Environmental impacts, Fin.

1. Introduction

Producing power by the combustion of fossil fuels is one of the most important factors of air pollution in the world. Nowadays, due to the descending rate of fossil fuel resources and the negative impacts of firing fuels on the environment, governments are tend to provide their electricity requirement, by renewable and sustainable energies, depends on their geographical situations [1].

From the sun, you can produce electricity in two ways: heat and light. Photovoltaic technology is the science of converting sunlight into electricity. Photovoltaic cells consist of materials called semiconductors. These materials convert part of the light into electricity, during a physical process when exposed to sunlight [2, 3]. Unfortunately, various ambient conditions lead to a drop in their electricity generation i.e. dust effect [4, 5], shading [6], aging [7]. In photovoltaic cells, from a physical point of view, the rise in temperature leads to a reduction in the electricity produced by photovoltaic cells. Each 1°C rising in the temperature of the PV panels, caused to degrade of the efficiency by about 0.45% [8-10] and 0.25% [11] for crystalline silicon and CdTe PV modules, respectively. Several methods have been proposed to overcome the problem, contain Phase Change Material (PCM), Nanofluid, thermoelectric, etc. The following literature review contains some of the researches, which includes the thermodynamics viewpoints of photovoltaic systems.

PCMs in the PV field are used in order to absorb the heat of the PV module and make a time delay in temperature rising of the PV cells. Khanna et al. [12] investigated numerically and experimentally of using RT25HC as PCM and a different configuration of fins. This substance has a melting point of about 25°C. Numerical parts of their study were made by Ansys 17.1 software. In that paper, the impact of different states of fins i.e. thickness and length were investigated. Finally, they reported the best case of fins in different states. Firoozzadeh et al. [13] experimentally compared three prototypes of photovoltaic modules as conventional PV panel, PV/PCM module, and PV module with both PCM and some fins. Poly-Ethylene Glycol 600 (PEG-600) was used as PCM in the mentioned study. That experiment was carried out in a maximum operating temperature of PV cells, namely 85°C. Finally, the results indicated that PV module with both PCM and fins has a better performance compared with the other prototypes, and the temperature difference of about 34°C was created between this case and conventional one. In a similar study, Firoozzadeh et al. [14] investigated the first and second laws of thermodynamics, when PCM and fins were simultaneously used as a coolant of the PV module. Moreover, they calculated the Rayleigh number for various cases of the experiment. Ahmed and Nabil [15], had an analysis of the effect of both fins and PCM, to enhance the performance of PV cells. They investigated several parameters, such as the temperature of PV cells, average Nusselt number and electrical efficiency. Finally, the results showed the significant effect of fins to improve the performance of PCM.

Sarhaddi et al. [16] investigated different parameters, i.e. ambient temperature, changes of PV array area, solar radiation intensity, and wind velocity, on the exergy efficiency of PV array. Sudhakar and Srivastava [17] were investigated both exergy and energy efficiency for a 36 W PV panel. They showed that by increasing the temperature of photovoltaic cells, the exergy losses of them increased too. Stougie et al. [18] were investigated the environmental, economic, and energetic assessment of power

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generation from some energy sources. Biomass, offshore wind farm, photovoltaic power plant and two kinds of the coal-fired power plant were studied. The results indicated that the offshore wind farm and Photovoltaic Park have the best energetic sustainability and environmental behavior of the others, respectively.

Using fin caused to increase the surface area as a determining parameter in heat transfer phenomena. Therefore, in heat transfer equipment i.e. heat exchangers [19-23], solar collectors [24], boilers [25], refrigerators [26], heaters [27], air conditioners [28], etc. using fin is very common. Hader and Al-Kouz [29] numerically investigated the performance of a PV/T system utilizing water-Al_2O_3 nanofluid and fins. They did their study by COMSOL software. The nanofluid was circulated in a pipe with very low inlet Reynolds (Re) number of 10 to 80. A number of fins were implemented on the pipe to increase the heat transfer area. Finally, the results showed that the overall efficiency of the PV/T system was increased by increasing the Re number and length of the fins. Zohri et al. [30] investigated mathematically on two different PV/T systems include: with and without fins, by means of a matrix inversion method. The value results illustrated that the PV/T system with fins has higher thermal and electrical efficiency than without one. Alfegi et al. [31] presented a numerical model for a double pass PV/T, with fins included. They investigated the effect of various air blowing rates, too. Finally, they reported the positive effect of both fins and air blowing on the output power of PV cells. From an economical viewpoint, Firoozzadeh et al. [32] presented a financial assessment of implementing aluminum fins on the back surface of PV modules and showed its economical justifiability. The influence of adding pin fins with different contact area was studied by Sedaghat et al. [33]. They numerically investigated the mentioned case. The study was based on the climate of Shiraz, Iran. Due to the temperature reduction in the PV module, it was reported that the proposed model, generated up to 4% more electricity, compared with the conventional one. Elbreki et al. [34], in a numerical research, used both EES and Ansys softwares in order to evaluate the thermal behavior of the PV modules. Various fin parameters have been assessed, e.g. height, thickness and spacing, on the output power of PV module. Results showed that the fins with more than 2mm thick, had no considerable impact on the efficiency of photovoltaic module. Other usual cooling methods have been also listed in Table 1.

Due to all of the renewable energies known as clean and environmentally friendly power sources, many scholars focused on assessing the environmental impacts of these sources [54-56].

According to the mentioned literature review, it is clear that most scholars are proposed difficult and costly ideas. The use of PCM, thermoelectric, and of course circulating nanofluids, are also costly ideas and need materials and equipment. So, in this paper, we experimentally focused on mounting fins, on the back surface of PV modules as a low cost and no need for maintenance method. Both energy and exergy analysis and the estimation of the entropy generation of conventional PV modules and proposed cases are also presented in the maximum operating temperature of PV modules, which is known as 85 °C. Calculating the exergy and entropy generation in the mentioned critical thermal condition was not done by any researcher, previously. Finally, the positive environmental impacts of using fins behind PV modules will be reported, too.

Table 1. Various methods for PV module cooling

Methods	Authors	Research type
Thermoelectric effect	Soltani et al. [35, 36]	Experimental
	Manikandan et al. [37]	Experimental
Air flow	Sarhaddi et al. [38]	Experimental and numerical
	Jha et al. [39]	Review
	Hosseini Rad et al. [40]	Experimental and numerical
Cooling by water	Hamdan et al. [41]	Experimental
	Tashtoush & Al-Oqool [42]	Experimental and numerical
	Kavoosi & Saidi [43]	Experimental
Nanofluid circulating system	Saffaian et al. [44]	Numerical
	Khanjari et al. [45, 46]	Experimental and numerical
	Firoozzadeh et al. [47, 48]	Experimental
	Al-Shamani et al. [49]	Experimental and numerical
	Sopian et al. [50]	Experimental
Phase Change Material (PCM)	Chandel et al. [51]	Review
	Qiu et al. [52]	Experimental
	Firoozzadeh et al. [53]	Review

2. Materials and Method

2.1 Experimental set-up

This experiment was done by two identical multi-crystalline PV modules with the maximum power of 60 watts. The full electrical characteristics of PV panels are presented in Table 2. To investigate the positive impact of fins on heat transfer, two cases are introduced as follow:

Case 1: Conventional PV module
Case 2: PV module with fins

In the second case of this experiment, 10 numbers of aluminum fins with 1 mm thickness, 50 mm space, were mounted at the back surface. Aluminum has a thermal conductivity of about 204 W/mK. Figure 1, represents a schematic of the case 2. The experiments were done in a room with an adjustable solar simulator.

In order to provide desired irradiation, two tungsten projectors with the power of 1 kW were used. A solar power meter of TES-132 was used to measure the value of emitted irradiation to the PV modules. It should be noted that experiments were done under two different irradiations of 420 W/m^2 and 630 W/m^2. More information about the effect of various irradiation on the output power of PV modules has been presented by Nasrin et al. [57].

In order to measure the amount of temperature variation of modules, the DS-18B20 digital thermometers were used. Mentioned sensors have an accuracy of 0.5°C and can measure the temperature range of -55 °C to +125 °C. Figure 2, shows the exact location of thermal sensors, behind the photovoltaic modules.

Table 2. Main characteristics of PV modules of this experiment [58]

Module characteristics	Value
Company	Yingli Solar / China
Power output (P_{max}) [W]	60
Module efficiency (η_m) [%]	14.4
Open-circuit voltage (V_{OC}) [V]	22.86
Short-circuit current (I_{SC}) [A]	3.44
Maximum operating temperature [°C]	85
Module type	Multi-crystalline

2.2 Governing equations

2.2.1 Energy analysis

The efficiency value which is written in different photovoltaic module's catalog is reported based on the Standard Test Conditions (STCs). These conditions are defined as solar irradiation of 1000 W/m^2, air mass of AM=1.5, and cell temperature of 25°C. Also, Normal Operating Cell Temperature (NOCT) is another common standard, which is less considered by scholars. Additional information about PV cell standards is available in [14]. In order to calculate the energy efficiency of photovoltaic modules, both input and output powers should be defined. So:

$$P_{out} = V_{OC} I_{SC} \tag{1}$$

and;

$$P_{in} = GA \tag{2}$$

where, I_{mp} and V_{mp} are current in (A) and voltage in (V) respectively. These parameters are obtained from the data-logger. Moreover, G is irradiation of the sun in (W/m^2) and A is the PV cells area in (m^2). Finally, the energy efficiency of photovoltaic modules (η) is calculated from the following equation:

$$\eta = \frac{P_{out}}{P_{in}} = \frac{V_{OC} I_{SC} FF}{GA} \tag{3}$$

where I_{SC} is short circuit current in (A) when voltage is zero, and V_{OC} is open circuit voltage in (V) when current is zero. Furthermore, in eq. (3), FF is the Fill Factor which is defined by eq. (4):

$$FF = \frac{V_{mp} I_{mp}}{V_{OC} I_{SC}} \tag{4}$$

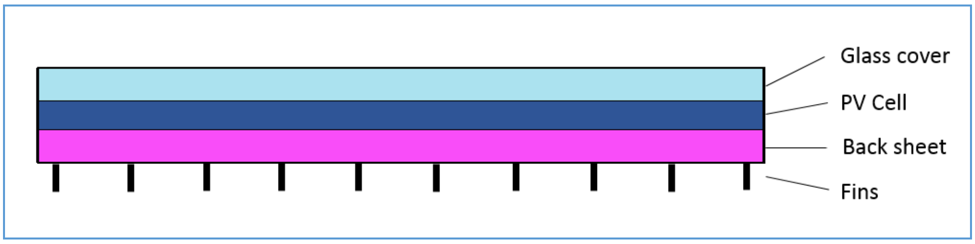

Fig. 1. A schematic of the suggested PV module with fins

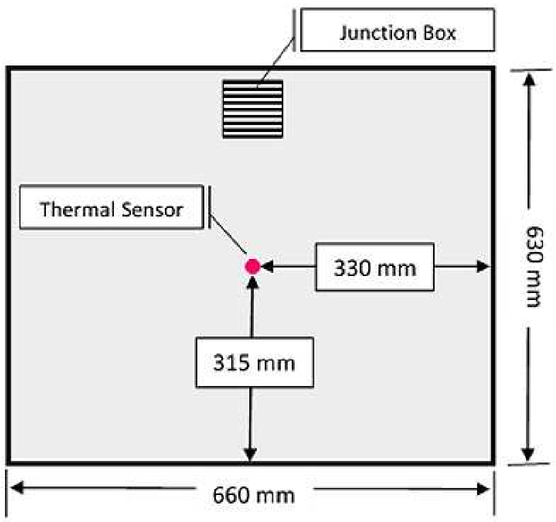

Fig. 2. Exact location of thermal sensor

2.2.2 Entropy generation

Exergy analysis is a thermodynamic assessment based on the Second Law of Thermodynamics. Exergy analysis can help us in modifying and optimizing designs [59].

For input exergy of a PV module, we have:

$$\dot{Ex}_{in} = \dot{Ex}_{sun} = (1 - \frac{T_{amb}}{T_{sun}})GA \tag{5}$$

where, T_{amb} is the ambient temperature, T_{sun} refers to the temperature of the sun which considered as 5770 K [60]. The parameters of G and A are solar irradiation in W/m^2 and the PV surface area in m^2, respectively. For the present research, the only output exergy is the electrical one as follow:

$$\dot{Ex}_{out} = \dot{Ex}_{ele} \tag{6}$$

The electrical exergy equals to electrical energy [61]. Therefore:

$$\dot{Ex}_{ele} = V_{OC} I_{SC} FF \tag{7}$$

The entropy generation can be calculated as the following equation [62, 63]:

$$\dot{S}_{gen} = \frac{\dot{Ex}_{lost}}{T_{amb}} \tag{8}$$

where $\dot{Ex}_{lost}$ is defined as below:

$$\dot{Ex}_{lost} = \dot{Ex}_{sun} - \dot{Ex}_{ele} \tag{9}$$

3. Uncertainty Analysis

In every experimental research, uncertainty analysis must be carried out, in order to eliminate systematic errors as much as possible [64]. If R defined as a function of independent linear parameters as $R = R(\upsilon_1, \upsilon_2, ..., \upsilon_3)$, the uncertainty for R can be calculated as [65]:

$$\delta R = \sqrt{(\frac{\partial R}{\partial \upsilon_1}\partial \upsilon_1)^2 + (\frac{\partial R}{\partial \upsilon_2}\partial \upsilon_2)^2 + ... + (\frac{\partial R}{\partial \upsilon_n}\partial \upsilon_n)^2} \tag{10}$$

In the above equation, δR is the uncertainty of R, $\partial \upsilon_i$ the uncertainty of parameter υ_i, and $\partial R / \partial \upsilon_i$ is the partial derivative of R with respect to υ_i. Finally, the maximum value for the uncertainty of parameters was measured to less than 3.3 %. Apart from this, the repeatability of experiments was confirmed, by performing each test two or three times.

4. Results and Discussion

4.1 Energy analysis

As already mentioned, by increasing the temperature of PV panels, their electrical efficiency is decreased. Figure 3 has been depicted to show the temperature and energy efficiency variation with time for different cases. As expected, the behavior of temperature and energy efficiency curves in all cases are inverse. It is clear that fins have been able to influence on reducing the panel's temperature for two irradiations of 630 W/m^2 and 420 W/m^2. In steady state conditions, the temperature differences of about 7.5°C and 4°C have been established for mentioned irradiations, respectively. This figure revealed the value of 2.34% and 2.68% additional in efficiencies for two mentioned irradiations, respectively. Also, it should be noted that this improvement was achieved at a very low cost.

4.2 Output Power

As already mentioned, an increase in the PV cell temperature leads to a decrease in their electricity generation. This fact is clearly exhibited in Fig. 4. According to the difference between the curves of Fig. 4(a), PV module equipped with fin, has about 25.35 % more output power compared with the conventional module. As clear, the power generation of PV module drops to one-half its nominal power, when the PV surface temperature reaches steady state. Furthermore, the value of reduction in output power for irradiation of 630 W/m^2 is more than 420 W/m^2, due to the higher surface temperature. More electricity generation leads to the decrease in return of investment, which is very interesting for investors of photovoltaic power plants.

4.3 Environmental assessment

In section 4.2, the output power generation was explored for the cases of both with and without fins. Accordingly, the environmental impacts of mounting aluminum fin at the back surface of PV modules are estimated by using the RETScreen software. This software is a powerful tool to technically evaluate both renewable and traditional power plants. Feasibility, return and risk of investment, output power analysis and all environmental impacts are evaluated. Here, the environmental impacts of a 20 kW PV power plant are estimated, with and without fin cases. Each case is studied for both natural gas and oil based fuel power plants. Table 3 shows the results of the considered cases. Altogether, the proposed PV module presents 25.4 % higher performance in environmental aspects. So, a PV power plant could be more environmentally friendly, when some fins are mounted at the back surface of the modules.

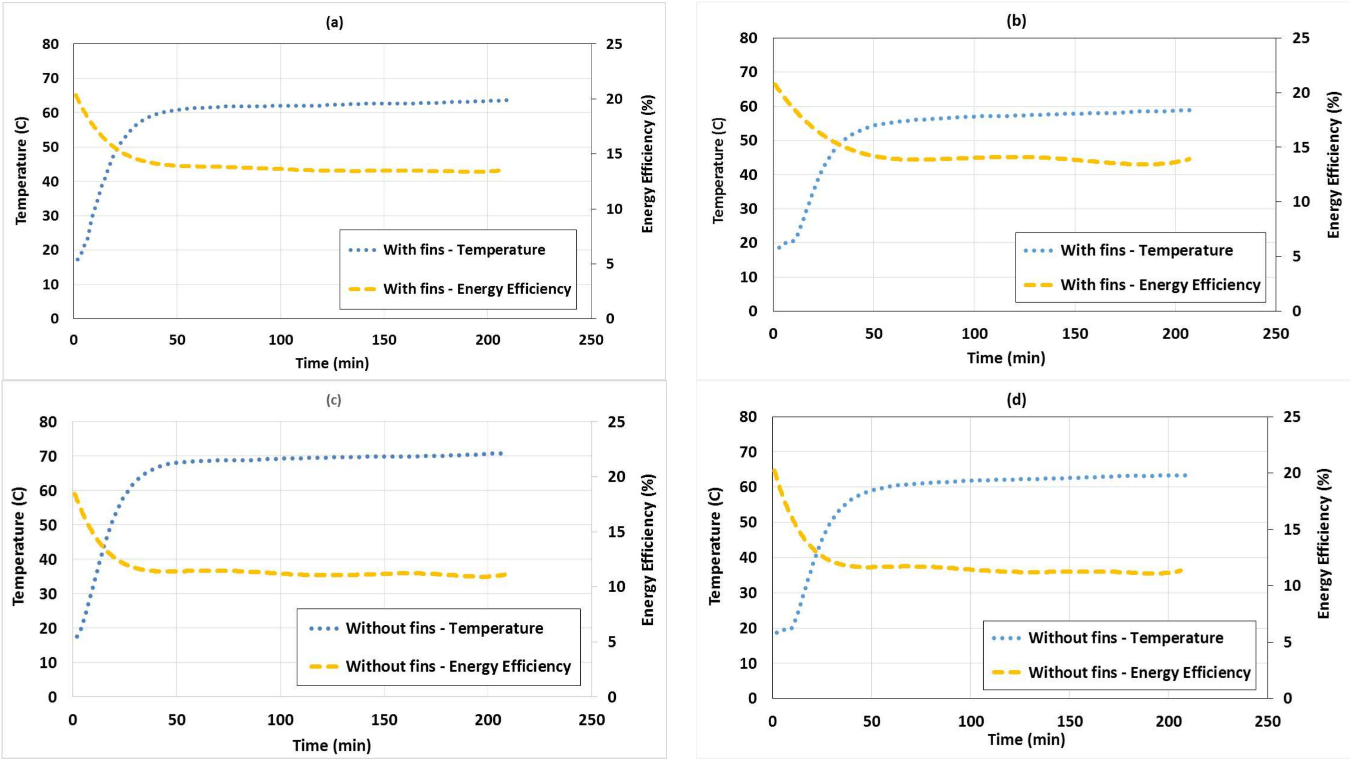

Fig. 3. Temperature and Efficiency variation with time for (a) with fins of 630 W/m², (b) with fins of 420 W/m², (c) without fins of 630 W/m² (d) without fins of 420 W/m²

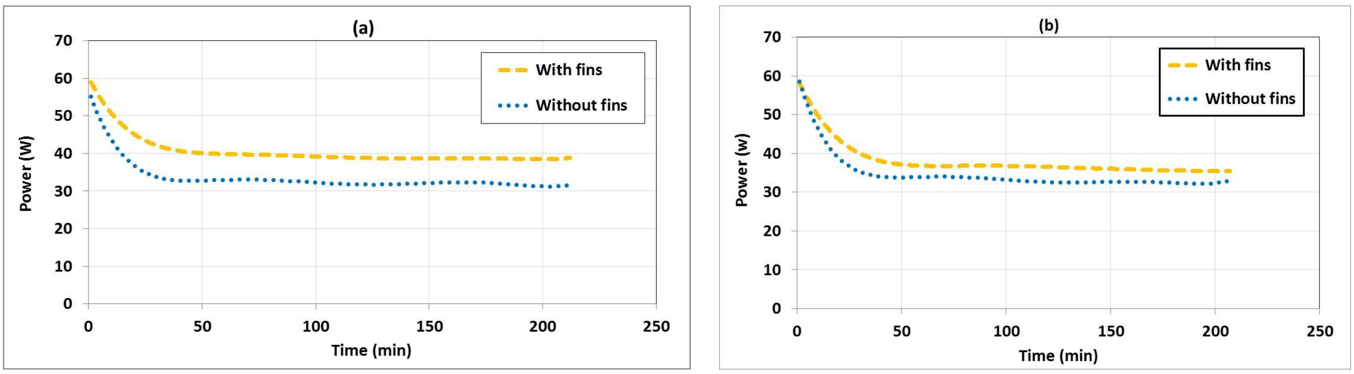

Fig. 4. Output power variation under irradiations of (a) 630 W/m² and (b) 420 W/m²

Table 3. Environmental impacts of implementing a 20 kW PV power plant, with and without fins PV modules

Environmental impacts	Natural gas			Oil		
	without fins	with fins	difference	without fins	with fins	difference
Annual CO2 reduction (tCO_2)	8.9	11.1	2.2	16.6	20.9	4.3
Liters of gasoline not consumed	3,804	4,771	967	7,143	8,958	1,815
Barrels of crude oil not consumed	20.6	25.8	5.2	38.7	48.5	9.8
Hectares of forest to absorb CO_2	0.8	1.0	0.2	1.5	1.9	0.4

Table 4. Summary of the results of this study

	630 W/m²			420 W/m²		
	without fins	with fins	difference (%)	without fins	with fins	difference (%)
Final temperature	71.0 °C	63.5 °C	- 11.81	63.3 °C	58.8 °C	- 7.65
Energy efficiency	11.09 %	13.43 %	+ 21.1	11.22 %	13.57 %	+ 20.4
Entropy generation	0.582 W/K	0.566 W/K	- 2.8	0.388 W/K	0.372 W/K	- 4.3

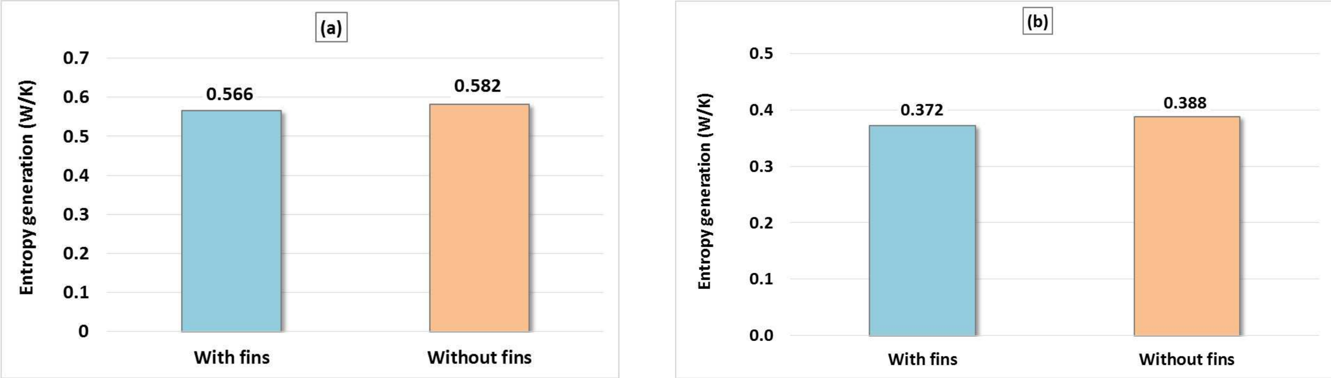

Fig. 5. Entropy generation for PV systems under irradiations of (a) 630 W/m^2 and (b) 420 W/m^2

4.4 Entropy generation

Entropy generation is another concept that is investigated in this paper. We know that in thermodynamics, Entropy is a property, which represents the irreversibility of a system. On the other hand, more entropy generation means more irreversibility. Figure 5 shows the amount of entropy production in various cases. With regards to this figure, mounting fin at the back surface of the PV module leads to a decrease in entropy generation. Accordingly, reduction in entropy generation of 2.8% and 4.2% for irradiations of 630 W/m^2 and 420 W/m^2 is seen, respectively.

4.5 Summary of results

In order to have a better sight of results, Table 4 is provided. According to this table, final temperature, both energy and exergy efficiencies and also entropy generation, achieved from the experiments accomplished were reported.

5. Conclusion

In order to increase the output power of photovoltaic modules, mounting aluminum fins have been investigated experimentally. Also, thermodynamic analyses of conventional and modified PV modules have been done. As a conclusion, the results can be summarized as follow:

1- Temperature differences of 7.5 °C and 4.5 °C were achieved for an irradiations of 630 W/m^2 and 420 W/m^2, respectively.
2- From an energy efficiency viewpoint, at the end of tests, the difference of 21.1% and 20.4% were measured for 630 W/m^2 and 420 W/m^2, respectively.
3- Entropy generation as a criterion of the irreversibility of the system was calculated too. The reduction of 2.8 % and 4.3 % for irradiations of 630 W/m^2 and 420 W/m^2 were concluded, respectively, when fins were used on the back surface of PV module.
4- By means of RETScreen software, a comparison of environmental impacts between PV module with fin and the conventional one was carried out. It was found that for a 20 kW PV power plant, using aluminum fin leads to a reduction of about 4.3 tons CO_2 emission, or saving 9.8 barrels of crude oil, compared with conventional PV panels, annually.

Author Contributions

Author 1 planned the scheme, initiated the project and suggested the experiments; Author 2 conducted the experiments and analyzed the empirical results. The manuscript was written through the contribution of both authors. Both authors discussed the results, reviewed and approved the final version of the manuscript.

Conflict of Interest

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

Nomenclature

A	Area (m^2)	*Subscript*	
EX	Exergy (W m^{-2})		
FF	Fill factor	amb	Ambient
G	Solar irradiation (W m^{-2})	cell	Cell
I	Current (A)	gen	Generate
P	Power (W)	in	Input
PV	Photovoltaic	out	Output
S	Entropy generation (W K^{-1} m^{-2})	mp	Maximum power
T	Temperature (°C)	OC	Open circuit
V	Voltage (V)	SC	Short circuit
		sun	Sun
Greek symbols		ele	Electrical
η	Energy efficiency (%)	lost	Lost
Ψ	Exergy efficiency (%)		

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