Investigation Results and Analysis of Solar Cells Performance Enhancement by Cooling using Thermoelectric Cooling (TEC)

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Abstract: Solar energy received special attention and extensive studies were conducted to increase the efficiency of solar collectors and solar cells. One of the major problems of the operation of solar cells is the temperature rising which causes a reduction in the energy yield. The main objective of this work is to experimentally investigate the cooling effect of thermoelectric cooling devices (TEC) on solar cell performance. To overcome the rising temperature effect, the cooling by using the Peltier device is proposed and investigated. In this approach, the TEC cooling module is attached to the backside of the photovoltaic cell. It is assumed that the required power to run the TEC module is provided by the photovoltaic cell itself when the additional power obtained by the cooling is more than the needed power to operates the TEC device. The results show that the cooling of the tested PV cells/modules samples by using the Peltier TEC device was slightly enhanced the PV cells' performance. In our case of study for a 2Wp solar cell sample, the maximum temperature difference obtained due to Peltier cooling is about 5.3C° which produced an enhancement for the produced power and the open-circuit voltage by 7.02% and 2.64% respectively. However, the needed power to feed the Peltier element is significantly higher than the recovered power due to the Peltier cooling. The same trend was investigated for the tested samples of PV modules. So, the proposed combination of PV and Peltier cooling system was investigated to be economically not feasible regardless of the cost evaluation. Finally, the spatial effect and the proposed system can be improved significantly by altering and improving the performance of the Peltier element and the thermal characteristics of the solar cells/modules encapsulation material.

Keywords: PV module, Solar cells, Peltier device, Laboratory tests, thermoelectric devices, PV cooling, spatial effect.

1. INTRODUCTION

The world's vision nowadays is focused on the energy sources sustainability where the exciting new international reports show that the renewable energy now accounts for one-third of all global power capacity and the robust development in renewable energy capacity in the trend of decade-long continued in 2018 with global additions of 171 gigawatts, according to new data released by the International Renewable Energy Agency (IRENA) [1].

Up to date, the most comprehensive and reachable figures on renewable energy capacity indicate growth in all regions of the world, although at variable speeds. While Asia reached for 61% of the total new renewable energy installations and raised installed renewables capacity by 11.4%, progress was fastest in Oceania with a 17.7% growth in 2018. 8.4% growth was reached in Africa to be ranked in third place, and approximately two-thirds was from renewables as a percentage of all new power generation capacity added in 2018, which was led by emerging and developing economies, and the annual increase of 7.9% was bolstered by new additions from solar and wind energy, which accounted for 84% of the growth as stated in IRENA's annual Renewable Capacity Statistics 2019 [2].

All EU countries have adopted national renewable energy action plans showing what actions they intend to take to meet their renewables targets. These plans include sectorial targets for electricity, heating and cooling, and transport; planned policy measures; the different mix of renewables technologies they expect to employ; and the planned use of cooperation mechanisms [3].

Renewable energy in Germany is mainly based on wind, solar and biomass. In addition, Germany had the

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world's largest photovoltaic installed capacity until 2014, and it was ranked as the third with 40 GW in 2016. Also, it is the world's third country that has an installed wind power capacity with 50 GW, and second for offshore wind with over 4GW [4].

One of the most common technologies of sustainable energy generation is the photovoltaic (PV) systems which achieve the conversion process for the sunlight to usable electrical power. This type of energy technology, which is pollutant-free during operation, reduces global warming problems, lowers operational cost, and represents minimal maintenance and the highest power density compared to the other renewable energy technologies.

Understanding and minimizing technology risks associated with PV investments underpin the need for ongoing studies on operational performance and reliability of field-deployed systems. Indeed, such data is important to various actors along the solar PV value-chain; from institutions involved in basic research to those that are engaged in project development, system integration, field deployment and operations and maintenance (O&M) services (Quansah and Adaramola, 2018) [5].

Photovoltaic (PV) durability and reliability questions have attracted increased interest in recent years because of their technological and economic significance. Reliability is the ability to perform a required function for a given time interval and is often measured in terms of failure rate or as a probability for failure [5]. In contrast, durability relates to the time interval during which a system is performing its desired task and is in PV it is commonly measured as the degradation rate, the slow gradual loss of performance.

In this regard, solar energy has received special attention and extensive studies have been done to increase the efficiency of the solar collectors and solar cell. A major problem in the operation of a solar cell is the rising temperature which in turn causes the reduction of the energy yield.

In addition, a significant fraction of solar radiation gets converted into heat when it falls on the solar cell thus reducing its efficiency. Generally, for every degree of temperature rise, the performance of PV panels falls by 0.5%, depending on the used type of solar cells [6]. Therefore, the temperature regulation of solar cell power systems becomes important particularly for Middle Eastern countries that experience consistently high temperatures in order to improve solar cell efficiency.

Cooling the operating surface is a key operational factor to take into consideration to achieve higher efficiency when operating solar photovoltaic systems. Proper cooling can improve the electrical efficiency, and decrease the rate of cell degradation with time, resulting in maximization of the life span of photovoltaic modules. The excessive heat removed by the cooling system can be used in domestic, commercial or industrial applications [7].

Efficiency improvements in solar energy conversion systems must be made in order for this renewable energy technology to be a viable solution. To make it a viable solution, there is a need to find different means of solving this temperature problem, which must result in an increase of the overall conversion efficiency. Very few authors have tried to put together and conduct an extensive review of different technologies that can be used to cool the operating surface of solar panels with the aim of increasing the overall efficiency of the solar conversion system [8].

Any adequate technology selected to cool photovoltaic panels should be used to keep the operating surface temperature low and stable that should be simple, reliable and, if possible, enable the use of extracted thermal heat to enhance the overall conversion efficiency.

Considering this, a cooling procedure will be implemented in this work based on the thermoelectric devices effect (or Peltier devices).

Thermoelectric cooler (TEC) modules are solid-state heat pumps that work according to the effect of Peltier. When an electrical current is supplied, the devices are capable of cooling or heating and can be thermally cycled using a multitude of electronic control methods. Alternatively, they may be used to minimize the effects of temperature parameters on oscillator conditions of the stability, reference voltages and amplifier offsets by providing temperature control.

The proposed work concentrates on the improvement of the conversion process of solar radiation energy into electrical energy. This will be achieved by increasing the heat dissipation absorbed by the PV during operation conditions by experimentally investigating the cooling effect of thermoelectric devices on solar panels. The “cold” side of the Peltier device can be used to absorb heat from the back of the solar panel while increasing the heat transfer rate of the "hot'' side and hence the performance of the PV panel will be improved.

2. MATERIAL AND METHOD OVERVIEW

The University of Applied Sciences and Arts Ostwestfalen-Lippe in Höxter owns Photovoltaic-Cells and modules of different types, TEC elements, and all the other materials and measurement tools in its procurement department. The next section introduces an overview of the used components and tools in the experiments and analysis.

2.1. Components and Measurements Tools

2.1.1. Peltier Device (TEC)

As mentioned before, the thermoelectric cooler modules are, in essence, solid-state heat pumps that operate according to the Peltier effect. When an electrical current is supplied, the devices are capable of cooling or heating and can be thermally cycled using a multitude of electronic control methods. Alternatively, they may be used to minimize the effects of temperature coefficients on oscillator stability, reference voltages, and amplifier offsets by providing temperature control.

The table below shows the main parameters and specification of the used Peltier elements, where the "cold" side of the Peltier device is used to absorb heat from the back of the solar panel while increasing the heat transfer rate of the "hot'' side and hence the performance of the PV panel will be improved.

2.1.2. Photovoltaic Cells and Modules

The cooling effect of the thermoelectric devices has been investigated on this work for different technology types and sizes of solar cells and modules which are indicated below in Table **2**. The Table introduces the specification for the decided solar cells and modules obtained from the manufacturer's datasheets.

2.1.3. Heat Sink Devices

As discussed before, with Peltier elements, technically there is no way to get around the fact that the hot and cold sides are very close together. In practice, today's Peltier elements are around only 3 to 5 mm thick. This fact makes it particularly significant to efficiently conduct the heat to and from the elements. Technically, this is achieved by quietly large heat sinks or dissipaters with fans as shown in Figure **1**.

Actually, with each one of the Peltier elements, we need for fin fan Peltier holder kit in order to control the temperature values and to protect the Peltier device from damage. Table **3** below shows the main specifications of the used heat sink unit on this work.

2.2. Experimental Setup and Procedures (Methodology)

As stated before, the investigation of the cooling effect of thermoelectric devices on the enhancement of the energy yield of different types and sizes of solar modules was achieved in this work. The Peltier element has two sides, the hot side of the element is connected to the fin fan heat sink to enhance and achieve the heat extraction. The other side of the element, i.e. the cold side, is connected to the backside of the solar cell as shown in Figure **2**.

Table 1: Peltier Element specifications

Parameter	Unite	Value
Imax	[A]	9
Vmax	[Vdc]	36
Pc max	[W]	193.5
ΔTmax	[°C]	68
A	[mm]	40
A1	[mm]	44
B	[mm]	40
H	[mm]	2.8
L	[mm]	100
Wire	AWG	n/a

Table 2: Specifications of the Tested Solar Cells and Modules

Model	Electrical Specifications	
2V 5W Mini Polycrystalline Solar Cell 	Power (W)	2
	Voc(V)	7
	Isc (A)	0.4
	Dimensions (mm)	136 x 110 x 3 mm
NUZAMAS Poartable 5W – 5V Solar Cell MonoCrystalline 	Power (W)	5
	Voc(V)	5
	Isc (A)	1
	Dimensions (mm)	190mm X 220mm
STP-5Wp Monocrystalline 	Power (Wp)	5
	Voc(V)	20.37
	Isc (A)	0.19
	Dimensions (mm)	216 x 300
ASI-5WP amorphous Si thin-film 	Power (Wp)	5
	Voc(V)	22.8
	Isc (A)	0.4
	Dimensions (mm)	293 x 330
SM-10Wp Polycrystalline 	Power (Wp)	10
	Voc(V)	20.8
	Isc (A)	0.64
	Dimensions (mm)	438 x 238

Figure 1: Standard fin fan Peltier Heatsink holder kit for heat dissipation purposes.

Table 3: Heat Sink Cooling Fin Fan Peltier Holder Kit Specifications

Model Name	Specification	
Heat Sink Cooling Fin Fan Peltier Holder Kit	Fan Voltage	9V
	Fan Current	1.1A
	Fan Dimension	120(L)*120(W)*25(H) MM
	Heatsink Dimension	110(L)*90(W)*43(H) MM

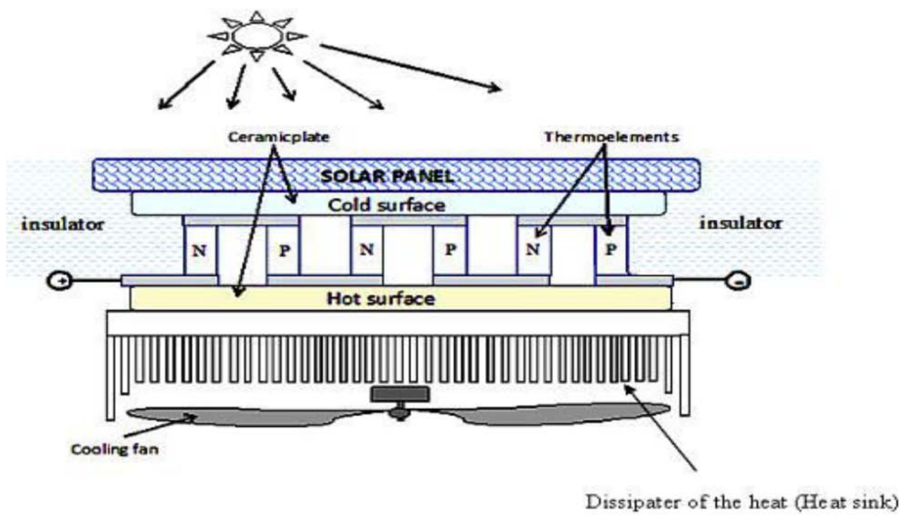

Figure 2: Schematic of the solar cell cooling system by using TEM.

The experiment was initially conducted for three small size solar modules of different technology types (5W Thin film and Monocrystalline type, and 10W Polycrystalline type), in order to investigate the cooling effect for these different types and compare them accordingly. Then the test was also done for two solar cells of 2W and 5W as well to check the cooling effect on the solar cell level.

The experiments were performed at the University of Applied Sciences and Arts Ostwestfalen-Lippe, Department of Environmental Engineering and Applied Informatics, Section of Renewable Energies and Decentralized Energy-Supplying, Hoexter-Germany. In this experimental work, we have highlighted the effect of temperature on the performance of solar cells in addition to using the thermoelectric module for cooling and enhancement of the solar cells and modules performance.

2.2.1. Experimental Setup

Figure **3** shows the experimental setup and preparation of the solar components and the other

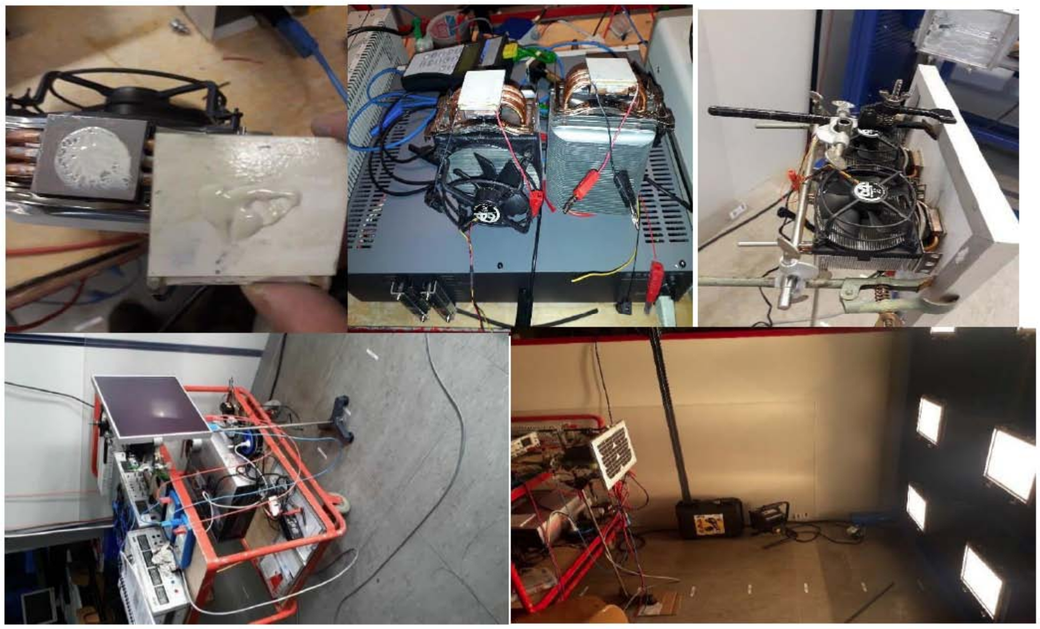

Figure 3: the experimental setup and preparation of the solar components and the other auxiliary tools of the experiments work.

auxiliary tools of the experiments work. The preparation of the Peltier element involves adding good thermal conductivity adhesive material of a certain low thickness which should be uniformly distributed among the surface of the TEC device in order to ensure efficient heat dissipation from the solar cells/modules via the heat sink.

The Peltier element and the heat sink installed and attached to the back of the solar cells/modules by the appropriate fixation stand rods and the stand kit of the installed solar module and Peltier element has oriented and directed toward the halogen lamps. The distance between the stand and the lamps was determined according to the decided solar radiation and the measurement tools of the radiation, temperature, voltage and current readings were installed in order to obtain the investigated parameters. In addition to this, the connection of the DC power sources to the Peltier and fans was also provided.

2.2.2. Experiment and Measurement Procedures (Methodology)

The experimental procedures of the work can be listed as the following:

1. Peltier elements characteristic identification was achieved by feeding the Peltier element with variable DC power supply, by varying the feeding power of the Peltier elements, the corresponding hot and cold side temperatures for all the existed TEM elements have been documented. The introduced analysis from the obtained curves gives a clear indication of how these modules work and which point of operation will be used more efficiently to proceed with the next steps.

2. The effect of the temperature on the solar cell characteristics was investigated by exposing the solar cells/modules to the direct radiation of the halogen lamps until the temperature of the tested solar cells/modules increased and the I-V curve in different temperatures showed the effect of the temperature on the solar cell characteristics.

3. After reaching a specific relatively high temperature, the halogen lamps were switched off, which let the solar cells/modules to be cooled naturally and with Peltier device cooling. The gradual reduction in the temperature values were recorded for every specific period of time (the 30s as an example) until reaching the saturation temperature. The corresponding voltage, current and power values of the module were also recorded synchronously at that time. As well as, the results of this step were compared. DC power supply fed the Peltier devices with the needed power directly after halogen lamps were switched off.

4. The temperature and power difference between steps 3 and 4 indicate the cooling benefits of the Peltier element on the PV performance enhancement.

5. The previous steps were conducted for solar cells/modules of different types and sizes in order to enhance the reliability of the obtained results.

6. Further analysis, results clarification, and suggestions will be documented.

3. RESULTS AND DISCUSSION

As stated before, in this experimental work, we have highlighted the effect of temperature on the performance of solar cells in addition to using the thermoelectric module for cooling and enhancement of the solar cells/modules performance. The upcoming sections introduce the detailed result analysis of the obtained experimental measurements.

3.1. Peltier Measurements

Two identical Peltier elements were used in this work. In the first steps of measurements, the Peltier devices output temperature difference behavior with respect to the increasing power that was consumed by them was studied and represented as shown in Figures **4** and **5**. The figures indicate that by increasing the power supply (P) to the element, the temperature difference (ΔT) was increased up to a limit at which the heat sink can dissipate the heat from the hot side without destroying the Peltier element.

The figures above show that the maximum obtained temperature difference was around 73C° at a power of 88.8W consumed by the TEC.

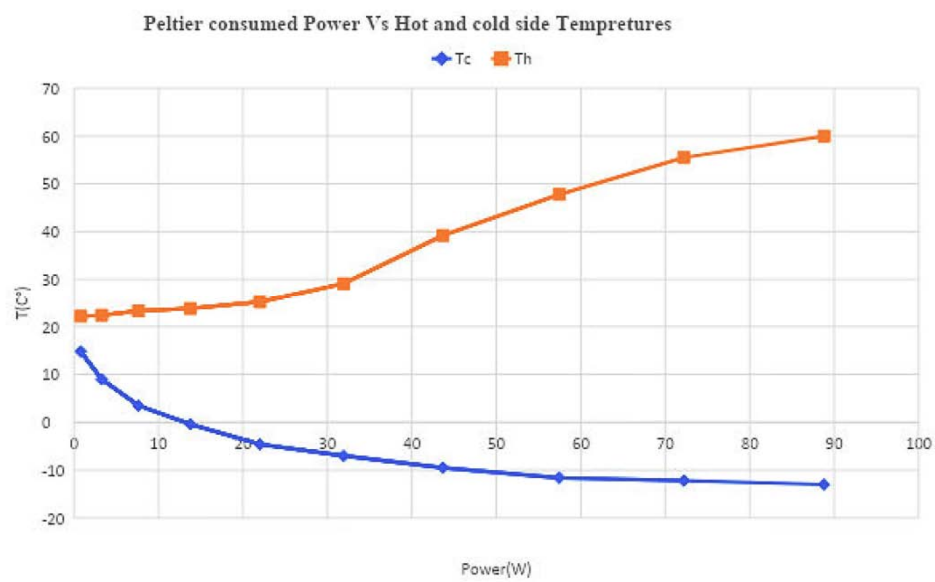

Figure 4: Peltier Power versus Hot and cold side Temperatures.

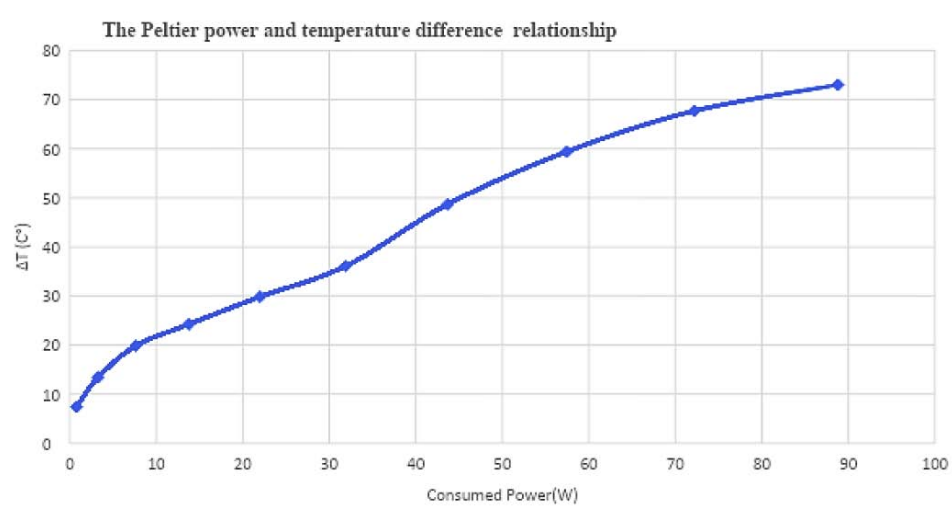

Figure 5: The Peltier power and temperature difference relationship.

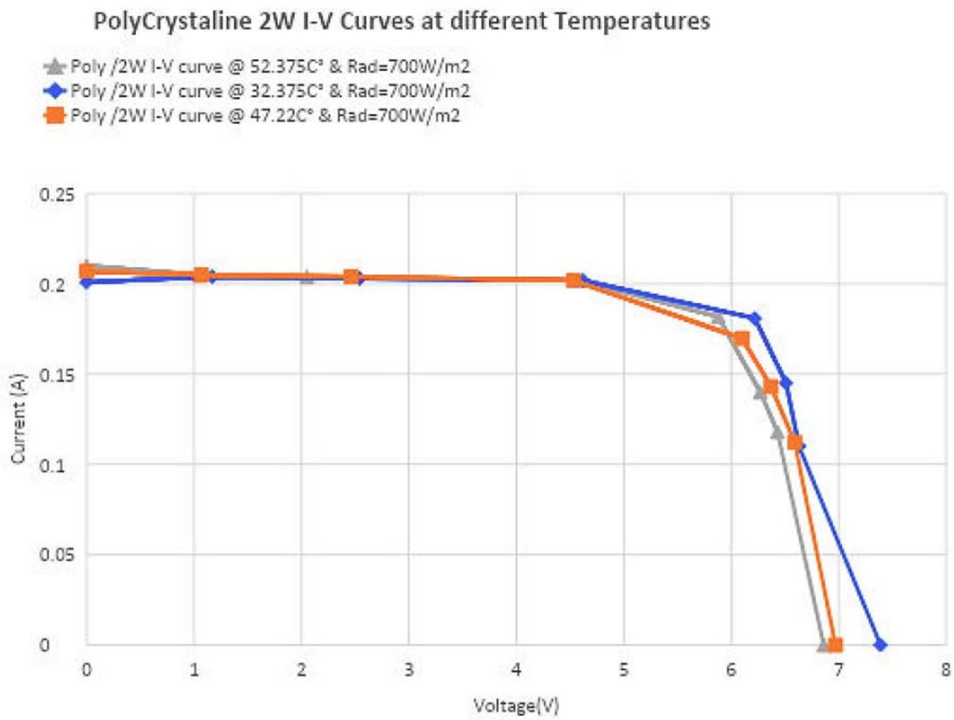

Figure 6: I-V Curves of the solar cell under different temperatures.

3.2. Effect of the Temperature on the Solar Cell Characteristics

The current-voltage (I-V) curve characteristic of solar cells are usually affected by temperature variations. In fact, by increasing the temperature, the magnitude of the current produced slightly increased, while the voltage of the cell reduced linearly with the temperature increase. The increase in current occurs due to the growth in the number of the carriers generated thermally in the solar component.

The overall effect of the temperature rise is the decrease in the produced power and accordingly the decrease in the overall efficiency of the solar cell as shown in Figure **6**. The obtained curves measurements are referred to the Polycrystalline solar cell type of 2W maximum power, the same behavior has been noticed obviously for the rest of the tested cells and modules.

3.3. Results and Analysis of the Peltier Cooling Effect on the Enhancement of the Solar Cells/Modules Performance

The cooling effect of the Peltier element on the performance enhancement of the solar cells/modules is summarized simply in investigating and comparing the obtained electrical characteristics of the solar cells/modules in relatively high-temperature values with and without Peltier cooling. This was achieved by maintaining the same controlled experimental and operation conditions.

In the beginning, the value of the power provided to Peltier element attached to the back of the solar cells/modules gradually increased. Simultaneously, the enhancement on the performance of the solar modules was monitored in order to obtain the threshold point at which the improvement can be obviously observed and evaluated. The open-circuit voltage (Voc), short circuit current (Isc), maximum power voltage (Vmp) and current (Imp) were measured for every step of time and for all tested samples with and without cooling effect.

Because of relatively different results of the measurements for solar cells and modules, the results and analysis of the obtained measurements are divided into two sections, the first one is related to the solar cell size and the second is concerned with the solar cell module level.

3.3.1. Peltier Cooling Effect on the Enhancement of the Solar Cell's Performance

The two tested solar cells are defined previously. The first one is the polytype of 2W power capacity and the second one is monotype of 5W power capacity. The two solar cells have been investigated and they have relatively the same behavior, so it will be enough to introduce the analysis of the results of the 2W solar cell in detail.

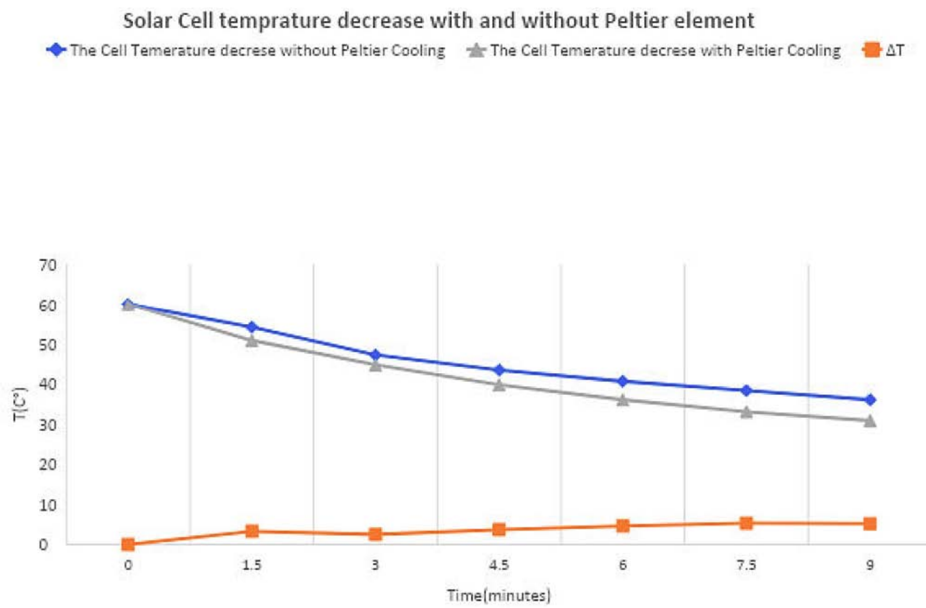

Figure 7: Solar Cell temperature decrease vs time with and without Peltier element.

Because the area at the back of the solar cell was occupied by the Peltier's heat sink unit, a maximum one Peltier device could be attached to the backside of the solar cell. Then the solar cell was directed toward the halogen lamps and placed at a distance of 150cm from the lamps in order to obtain observable saturated values of the temperature that was increasing and decreasing with the time. The obtained radiation from this distance was measured to be around 700W/m² and the readings were taken after every 1.5 minutes. The temperature of the solar cells was increased until reaching 60C° and then cooled down with and without the Peltier device.

Figure **7** shows the behavior of the temperature decreasing curves with and without Peltier cooling and the temperature difference caused by the cooling.

The corresponding open-circuit voltage (Voc) and the power production enhancement on the solar cell performance are represented by the difference between the production by the solar cell with and without the Peltier cooling at every step of time as indicated in Figures **8** and **9**.

As indicated in Figures **8** and **9**, the maximum obtained temperature difference is about 5.3C°. This temperature difference accordingly produces the maximum power and voltage difference of 0.078W and 0.19V, respectively, which is equivalent to an enhancement of 7.02% for the power produced and 2.64% of the open-circuit voltage. The obtained decrease in the operating temperature of the solar cell causes an increase in the power and voltage produced by the cell, but this enhancement does not necessarily mean that the cooling by the Peltier element is efficient because the consumed power by the Peltier element, in this case, is about 12W while ignoring the heat sink power consumption. This value is very high with respect to the power obtained by the cooling of the cell, which clearly indicates that the cooling by this mechanism is not economically feasible. This may be referred mainly to the low efficiency and COP values of the Peltier element, the high percentage of waste heat which was dissipated by the heat sink, and the high thermal insulation material at the back of the solar cell, in addition to the other losses may be caused by the adhesive material and connections.

3.3.2. Peltier Cooling Effect on the Enhancement of the Solar Module's Performance

The three tested solar modules of different sizes and technology were defined previously. The first one is the polytype of 10W, and the second one is the monotype of about 5W, and finally the amorphous thin-film type of 5W power capacity. The three solar modules have been investigated and have relatively the same behavior, so it will be enough to introduce the analysis of the results of the 5W thin film solar cell type in detail.

Here we could have a maximum of two Peltier device, which were attached to the backside of the solar module, because of the high area occupied by the heat sink required for each element. The hybrid solar module and Peltier element were then directed towards

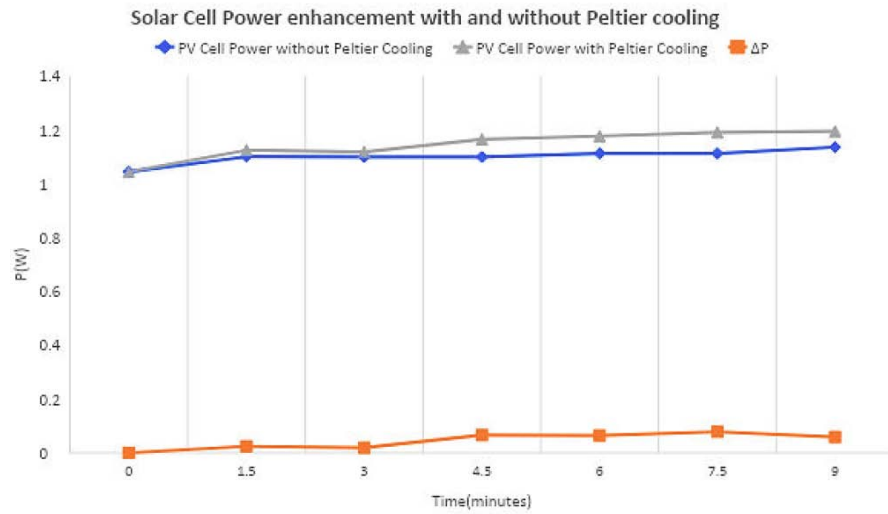

Figure 8: Solar Cell Power vs time curves with and without Peltier element.

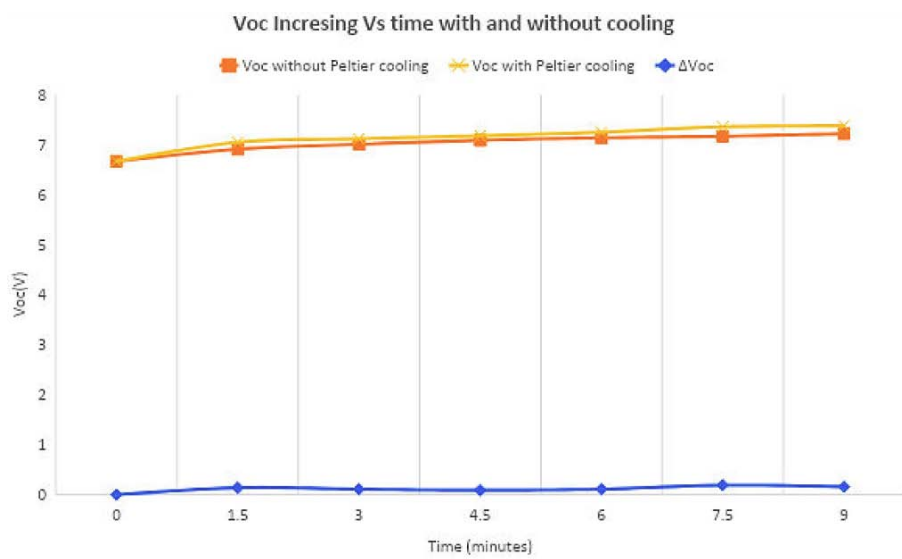

Figure 9: Voc Increasing Vs time with and without cooling.

the halogen lamps and placed at a distance of 125cm from the lamps in order to obtain observable saturated values of the temperature which was increasing and decreasing with the time. The obtained radiation from this distance was measured to be around 1000W/m². The readings have been taken after every 2 minutes and the temperature of the solar modules was increased until it reached 65C° and then cooled down with and without the Peltier device.

Figure **10** shows the behavior of the temperature decreasing curves with and without Peltier cooling and the temperature difference caused by the cooling.

The corresponding open-circuit voltage (Voc) and the power production enhancement on the solar module performance is represented by the difference between the production of solar module with and without the Peltier cooling at every step of time as indicated in Figures **11** and **12**.

As noticed from the figures, the maximum obtained temperature difference is about 7.5C°. that temperature difference accordingly produces maximum power and voltage enhancement of 0.085W and 0.89V, respectively, which is equivalent to an enhancement of 4.67% for the power produced and 4.34% of the open-circuit voltage. This shows that the obtained decrease in the operating temperature of the solar cell causes an increase in the power and voltage produced by the cell, but this enhancement does not necessarily means that the cooling by the Peltier element is efficient because the consumed power by the Peltier element, in this

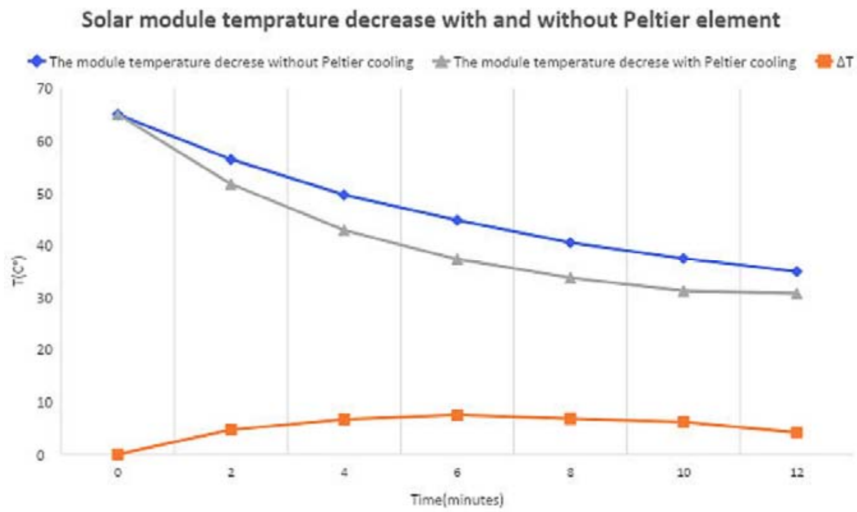

Figure 10: Solar module temperature decrease with and without Peltier element.

case, is about 10W per element while ignoring the heat sink power consumption. This value is very high with respect to the power obtained by the cooling of the cell, which clearly indicates that the cooling by this mechanism is not economically feasible. This may be referred mainly to the low efficiency and COP values of the Peltier element, the high wasted heat percentage which was dissipated by the heat sink, and the high thermal insulation material at the back of the solar cell. In addition to these, there might have been other losses caused by the adhesive material and connections as we mentioned before.

In general, the performance enhancement in solar cells is more efficient due to the low thermal insulation of the encapsulation material of the cells when compared with the solar modules.

Figure **13** shows the thermal photos that were taken with the Flir thermographic camera which demonstrates clearly that the cooling produced by the Peltier element is not distributed evenly over the surface of the solar cells/ modules, and since the efficient cooling will not be obtained. So, the spatial distribution of the Peltier for the larger size PV modules may be improved by altering the thermal characteristics of the encapsulation materials in order to efficiently determine the numbers and the appropriate positions of the Peltier elements.

3.5. Uncertainty Analysis

Tables **4** to **6** represent some specifications of the measurement tools that were used in this work. Moreover, these tables can be used to introduce an indication of the certainty of the obtained results. In addition, the measured parameters in this work depend mainly on the environmental parameters like temperature and radiation. So, the obtained results depend on each other, where the temperature and radiation were simultaneously measured with voltage

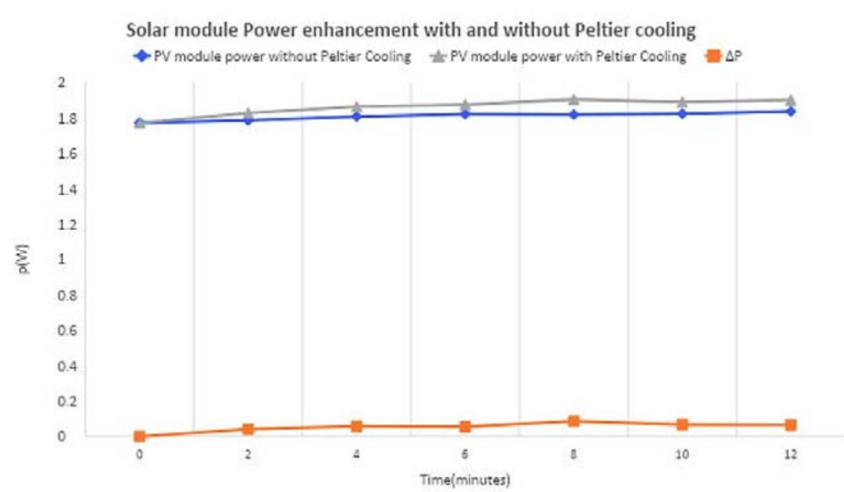

Figure 11: Solar Module Power curves with and without Peltier element.

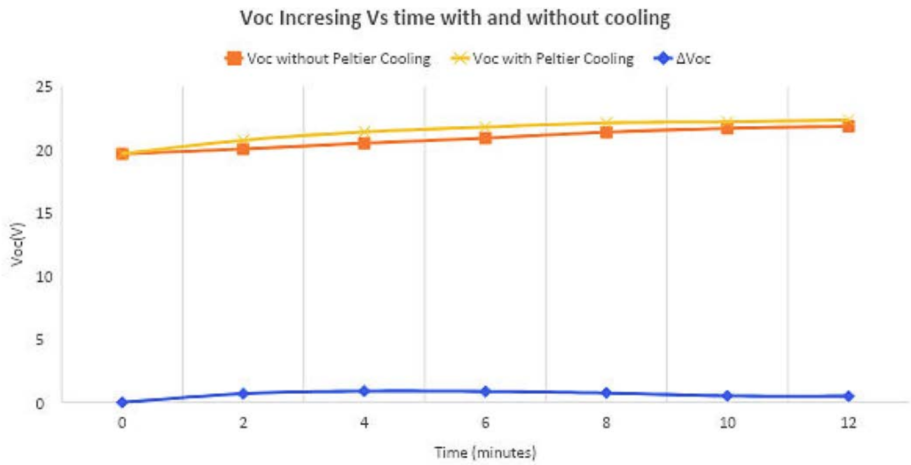

Figure 12: Voc Increasing Vs time with and without cooling.

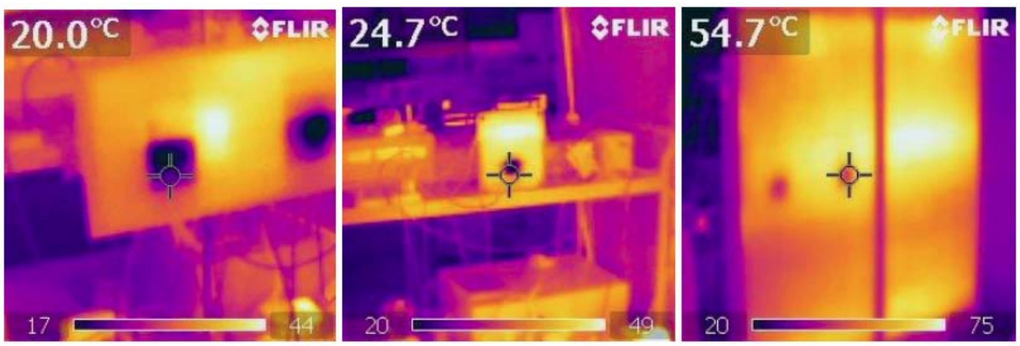

Figure 13: Thermal photos taken by Flir thermographic camera (Spatial effect for Peltier Devices).

and current of the PV cells/modules in order to obtain the I-V curve characteristics for each module type. During measurement of specific electrical parameters, the reading continuously changed with the time because the radiation and temperature values are difficult to be definitely stable.

The temperatures were measured using E NiCr-CuNi class one thermocouple type (±1.5 c), which were connected to a digital temperature indicator in addition to the thermographic camera. Total insulation was measured by Spektron 210 Pyranometer ranged of 0 – 1500 W/m² with Uncertainty < ±5% of reading. The analysis of the uncertainty was evaluated using the following procedure (Holman, 2012) [8,9]:

4. CONCLUSIONS

In this experimental work, we have emphasized the effect of temperature on the performance of solar cells. In addition, the cooling effect of the thermoelectric devices has been investigated for different technology types and sizes of solar cells and modules using the thermoelectric devices. For cooling and enhancement

Table 4: I-V Digital Multimeter I-V Measurements Tool's Specifications

DC Voltage Measurements			DC Current Measurements		
Range	Resolution	Accuracy	Range	Resolution	Accuracy
400 mV	100 µV	±0,5% v.M. + 2 St.	400 µA	0,1 µA	±1,0% v.M. + 3 St.
4 V	1 mV	±1.2% v.M. + 2 St.	4 mA	1,0 µA	±1,5% v.M. + 3 St.
40 V	10 mV		40 mA	10,0 µA	
400 V	100 mV		400 mA	100,0 µA	
600 V	1V	±1.5% v.M. + 2 St.	4A	1,0 mA	±2,5% v.M. + 5 St.
			10A	10,0 mA	

Table 5: Radiation Meter Specifications

Model	Spektron 210!
Measuring range %	0 - 1500 W / m² %
Sensor Type%	Monocrystalline Cell (13 mm / 33 mm) %
Sensor accuracy%	± 5% %
Electrical output Approx.%	75 mV at 1000 W / m²%
Sensor structure %	Laminated in Novaflon and EVA foil%

Table 6: Thermometer Specifications

Thermocouple Type	Class	Temperature Range	Deviation Limit
E NiCr-CuNi 1	1	-40 ° C to + 800 ° C	1.5 ° C or 0.0040 x | t |
	2	- 40 ° C to + 900 ° C	° C or 0.0075 x | t |

Temperature sensors accuracy (each) = ±1.5%.
Pyranometer accuracy = ±5%.
Ambient Air temperature sensor accuracy =±0.5%.
Multimeter Circuits measurement of the voltage and current accuracy = ±1.5%.
Uncertainty value of the experiment is evaluated by =

$$\sqrt{\begin{array}{l}(\text{uncertainty of the temerature sensors element})^2 + (\text{uncertainty of Spektron radiation meter})^2 + \\ +(\text{uncertainty ambient air temperature Sensor})^2 + (\text{uncertainty of Circuits measurement Multimeter tool of the voltage and current})^2\end{array}}$$

Based on the above equation, the measurements uncertainty of the experiment is about 5.45%.

of the solar cells/modules performance and life expectancy, the following results have been concluded:

- The temperature rising of the PV cells/modules causes a decrease in the produced power and accordingly the efficiency and the performance of the solar modules/cells.
- The cooling of the tested PV cells/modules samples by using Peltier thermoelectric devices have enhanced the performance of the PV samples.
- The enhancement for the PV cells/modules by using Peltier devices is not technically efficient because, as seen in our case of study, the needed power to feed the Peltier element is significantly higher than the recovered power due to the cooling.
- In our case of study, the hybrid PV/TEC system was tested and addressed to be economically not feasible regardless of the proposed system cost evaluation.
- In general, the performance enhancement of solar cells is more observable and efficient than the solar modules due to the low thermal insulation of the encapsulation material of the cells.
- The thermal photos that were taken with the Flir thermographic camera demonstrate clearly that the cooling produced by the Peltier element is not distributed evenly over the surface of the solar cells/ modules surface and this is one of the reasons that make this cooling system to be not efficient.
- Finally, such a hybrid system is more efficient in the locations of hot climatic conditions where the ambient temperature is high and at circumstances where the heat removal due to convection is problematic and cooling of the panel is noteworthy and necessary.

5. FUTURE WORK AND RECOMMENDATIONS

An intensive economic evaluation is required for the different thermal management techniques in order to determine if the extra capital cost of the additional arrangement is certainly compensated by the additional power savings. Then the suitability and effects generated by the systems should be addressed at the social and environmental stages.

As an example, the performance efficiency of the Peltier element, the thermal characteristics of the encapsulation material, and the use of heat dissipation can be improved to enhance the capability of this technique.

It is expected for these systems to have a relatively long payback period considering the PV panels' initial cost and the extra cost of the cooling preparations. Fortunately, the economic feasibility is expected to be enhanced if the thermal energy removed from PV panels can be efficiently used for ventilation, space heating, or hot water and other applications, Therefore, further work should be directed from the viewpoints of economic estimation and life cycle assessment.

NOMENCLATURE

Acronyms

STC = Standard Test Conditions

DR = Degradation Ratio

PV = Photovoltaic

FF = Fill Factor

Symbols

T = Temperature *[°C]*

E = irradiance in W/m²

ϑ = Measured Temperature.

P = Power

V = Voltage

I = Current

Greek Letters

Δ = Drop

η = Efficiency [%]

Subscripts

mpp = Maximum Power Point

Meas = Measured

Max = Maximum

sc = Short Circuit

Manu = Manufacturer

oc = Open Circuit

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