The Temperature Influence in the Photovoltaics Panels Performance

João P. M. Caleiro

Instituto Superior Técnico, Universidade de Lisboa, Lisbon, Portugal

***Abstract* — This work investigates the effect the temperature will have on photovoltaic cells. Using the *COMSOL Multiphysics®* software, several computational simulations were made in order to study this effect. The simulations made for silicon, CIGS, CdTe and perovskite cells show that, out of all the cells, perovskite are the least negatively affected by an increase in temperature. In terms of the silicon's properties, it has been found that the decrease in band gap with the temperature will cause a decrease in the value of the open circuit voltage of the cell, which negatively impacts the maximum power and efficiency of the cell, while the increase in the extinction index with the temperature will lead to an increase in the short circuit current which will prove beneficial to the performance of the cell. Alongside this, a study of various cooling technologies was also conducted, where advantages and disadvantages of each method are analyzed.**

***Index Terms* — Solar Cells, Temperature, Semiconductors, Cooling**

I. INTRODUCTION

An increase in the human population and activity has led to a rise in the world energy consumption and global energy demand. Fossil fuels make up the world's main primary energy sources, but they possess problems such as their scarcity and the pollution that forms as a result of their combustion. Photovoltaic systems are able to convert sunlight into electricity thereby providing a clear and renewable alternative to fossil fuels. The efficiency of the process of the conversion of sunlight into electric will depended on various environmental factors such as the irradiance, the temperature, and the wind speed, so it becomes important to better understand the impact of these parameters in order to be able to maximize the performance of the photovoltaic systems. For the case of the temperature, it is well known that, with its increase, the solar panel will see a reduction in the open circuit voltage (V_{OC}) and consequently in the maximum power (P_{MP}) which will negatively impact the performance of the photovoltaic system. Temperature is also associated with other drawbacks, such as the potential overheat of the solar panel, which can cause hot spots which will degrade the performance of the panel and lower its lifetime. The main objective of this paper is to study the effect the temperature will have on solar cells. To do this, a theoretical analysis for the operation of a solar cell was conducted and several computational simulations were done in order to draw conclusions. Furthermore, a study of several cooling technologies was done to understand how to best combat the problem of the increasing temperature of the photovoltaic system. This article is structured in the following way: section I provides an introduction and provides a brief overview of the problem under study. Section II consists of a review of the literature on the subject. Section III provides a theoretical framework of the effect on the temperature. Section IV shows the computational simulations, section V showcases cooling methods that may be employed, and section VI concludes the paper.

II. LITERATURE REVIEW

The temperature will not have the same impact on every type of solar cell, affecting them in different ways, both in overall performance and in specific solar cell's parameters.

A. Monocrystalline Silicon Solar Cell

With an increase in temperature, monocrystalline silicon solar cells will experience a slight increase in the short circuit current (I_{SC}) and a decrease in the open circuit voltage and maximum power and efficiency [1].

B. Polycrystalline Silicon Solar Cell

Polycrystalline silicon solar cells behave very similarly to monocrystalline cells, the only difference being that they perform slightly worse in warm weather.

C. Amorphous Thin-Film Silicon Solar Cell

Unlike crystalline solar cells, amorphous silicon solar cells cannot be characterized by temperatures coefficients since the temperature dependence is typically non-linear and, in fact, some amorphous solar cells may even have an increase in efficiency for a certain range of temperatures higher than 25 ºC [2]. They tend to have better performances at high temperatures than crystalline solar cells [3] and, unlike those solar cells, the fill factor (FF) and short circuit current show significant increases with an increase in temperature. Amorphous cells tend to have relatively little temperature dependence once they are operating in an equilibrated state, however they will have a strong temperature dependence if the photovoltaic system experienced a sudden increase in temperature.

D. Multi-Junction Solar Cell

Multi-junction solar cells experience the typical decrease in open circuit voltage and maximum power, with the increase in temperature, although this decrease will not be as pronounced as is the case in single junction cells, making them a good choice for a photovoltaic system that is expected to operate in high temperatures. When it comes to the short circuit current, the increase in temperature can cause either a decrease or an increase in the value of I_{SC} depending on which layers are used in the multi-junction cell [3].

E. CIGS Solar Cell

With an increase in temperature in a CIGS solar cell there will be a slight decrease in the short circuit current, fill factor and quantum efficiency and a significant decrease in open circuit voltage accompanied by a decrease in the output power and efficiency [5]. In order to lower the negative impact the temperature will have in a CIGS cell, it is also possible to install a luminescent down shifting (LDS) layer on top of the photovoltaic material which will improve the performance of the CIGS cell for high temperature.

F. CdTe Solar Cell

An increase in the temperature of a CdTe cell causes a slight increase in the short circuit current and a decrease in the open circuit voltage, fill factor, maximum power and efficiency. For CdTe solar cells, the temperature coefficient for the V_{OC} is extremely similar to that of silicon-based cells, [6] however the overall efficiency coefficient is less pronounced, meaning that CdTe solar cells are not as affected by an increase in temperature as either monocrystalline or polycrystalline solar cells.

G. Organic Solar Cell

For organic solar cells, the open circuit voltage decreases almost linearly with the temperature while the short circuit current will increase slightly with it until it reaches a maximum value of saturation and will subsequently decrease [7]. Unlike most types of solar cells, in organic cells the efficiency will actually increase with the temperature up until about 320 K, after which it will decrease [8]. Figure 1 shows how, for various irradiances, the efficiency of an organic solar cell varies with the temperature.

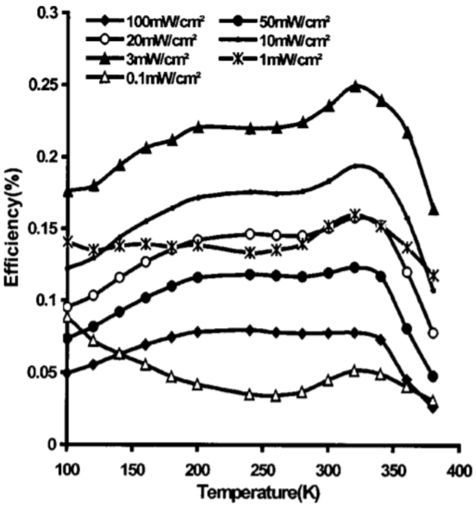

Figure 1 - Efficiencies of an organic solar cell in function of the temperature, for various irradiances [8]

H. Perovskite Solar Cell

Perovskite solar cells based on $CH_3NH_3PbI_3$ have been found to exhibit hysteresis in the I-V characteristics, meaning that the parameters and efficiency of the solar cell will be different depending if a forward scan (short circuit to open circuit) or a reverse scan (open circuit to short circuit) occurred. An analysis of the photovoltaic parameters in relation with the temperature, shows that hysteresis is observed at the temperature range of -20 ºC to +55 ºC, with a particular mismatch for the values of V_{OC} and FF. For both parameters, a reverse scan results in higher values and consequently the efficiency will be higher if a reverse scan occurred than it would be for a forward scan [9].

I. Quantum Dot Solar Cell

Lead sulfide (PbS) Quantum Dot solar cells experience a decrease in the open circuit voltage, fill factor and efficiency, with an increase of the temperatures above. The short circuit current and the diode ideality factor, on the other hand, do not seem to be affected by the temperature [10]. In the case of a heterojunction quantum dot solar cell, where titanium dioxide is used as the compact layer and PbS QD as the absorbing layer, there was a decrease in the I_{SC}, V_{OC}, and efficiency, with an increase in the temperature [11].

J. CZTS Solar Cell

A study [5] showed that for an increase in temperature, from 300 K to 360 K. of a CZTS cell there was a linear decrease in the open circuit voltage and efficiency and a slight increase in the fill factor and short circuit current. Compared with CIGS cells, CZTS solar cells tend to have better behavior at high temperatures as their normalized output power (and therefore their conversion efficiency) is higher than in CIGS cells.

K. GaAs Thin-Film Solar Cell

With an increase in temperature, the short circuit current of the GaAs cell will increase, the open circuit voltage will decrease, and the fill factor will be almost entirely independent of the temperature. When it comes to the I_{SC}, its temperature coefficient will more pronounced than in monocrystalline silicon cells, meaning that the I_{SC} will grow more with the increase in the temperature of the cell. For the V_{OC}, with the increase in temperature of the module, it will not decrease as much as the mono-Si cell, with the temperature coefficient being less than half it usually is in mono-Si cells [12]. Because of this, the P_{MP} will only decrease slightly with the temperature. A comparison between the P_{MP} of the GaAs and mono-Si cell in function of the temperature can be seen in Figure 2.

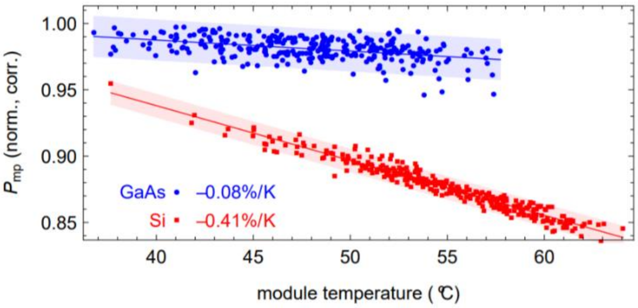

Figure 2 - *Normalized maximum power of a mono-Si and GaAs cell in function of the temperature* [12]

L. Dye-sensitized Solar Cell

Unlike most types of cells, in dye-sensitized solar cells, the recombination process in the active layer of the cell is roughly the same up until the temperatures of 40 ºC [13]. This in effect, means that the efficiency of the DSSC will only start to decrease when the cell will reach this temperature. The open circuit voltage will decrease with the temperature, having a more pronounced decay for temperatures higher than 40 ºC, since, from that point on, the recombination will increase. The short circuit current seems to remain the same for all temperatures.

III. THEORETICAL FRAMEWORK

A. Solar Cell Operation

The equivalent circuit of a solar cell can be seen in Figure 3, while the characteristic equation of the cell, that relates the current with the voltage, can be described in the following way:

$$I = I_{pv} - I_s\left(e^{\frac{V+IR_S}{n*\frac{kT}{q}}} - 1\right) - \frac{V + IR_S}{R_{SH}} \qquad (1)$$

where I and V are the terminal current and voltage, respectively. I_{pv} is the photo-generated current, I_s the reverse saturation current, n the diode ideality factor and R_S and R_{SH} are the series and shunt resistance, respectively.

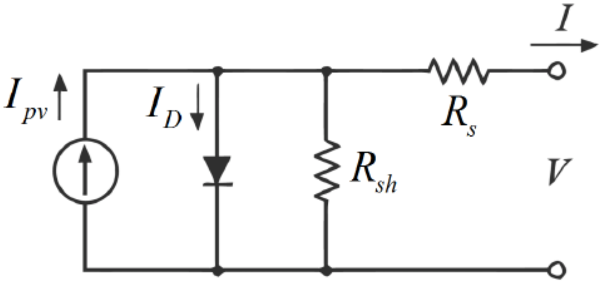

Figure 3 – *Equivalent Circuit of a Solar Cell [14]*

All of the parameters in the characteristic equation of the solar cell will be, in some way or another, affected by the temperature, but it will be especially significant for the reverse saturation current, I_s, which is given by:

$$I_s = q.A.n_i^2\left(\frac{D_p}{N_d}\frac{F_n}{L_p} + \frac{D_n}{N_a}\frac{F_p}{L_n}\right) \qquad (2)$$

where A is the area of the cell, n_i is the intrinsic carrier concentration, D_p and D_n are the diffusion coefficients of the holes and electrons respectively, N_d and N_a are the donor and acceptor concentrations respectively, L_n and L_p are the diffusion lengths of electrons and holes respectively and F_n and F_p are the finite recombination velocities of the electrons and holes. The intrinsic carrier concentration is the parameter in the above equation most affected by the temperature and is the only one discussed in this paper.

The intrinsic carrier concentration is an important parameter in the solar cell operation that is linked to the efficiency. In a condition of equilibrium, it is expressed as a function of the densities of electrons and holes, as can be seen in the following expression.

$$n_0 p_0 = n_i^2 \qquad (3)$$

With an increase in temperature, there will be an increase in the electron and hole densities, thereby causing an increase in the intrinsic carrier concentration. The intrinsic carrier concentration can also be expressed in the following way:

$$n_i^2(T) = N_C N_V e^{-E_g/kT} \qquad (4)$$

where N_C and N_V are the effective density of states in the conduction and valence bands, respectively, and E_g is the band gap. Both the effective density of states are dependent on the temperature, with N_C and N_V experiencing an increase with an increase in temperature. Expressing the equation for the characteristic equation of the solar cell in terms of the V_{OC} wields:

$$V_{OC} \approx \frac{kT}{q}\ln\left(\frac{I_{pv}}{I_s}\right) \qquad (5)$$

The increase in I_s will cause a decrease in the value of V_{OC} which is what is primarily responsible for the decrease in maximum power and efficiency of the cell with the temperature. Also affected, albeit slightly, is the I_{pv} which increases slightly with increasing temperature because of an increase in the number of thermally generated carriers in the cell.

B. External Factors

Since the exposure of solar cells to sunlight generates heat as well as electricity, their temperature will not be the same as the ambient temperature, meaning that, often, solar panels will be operating at higher temperatures than ambient temperature.

Other factors that will influence the temperature of the photovoltaic system include the wind speed, the wind azimuth angle, the tilt angle of the panel and the irradiance. For the case of the wind speed, its increase will lower the temperature of the panel. The tilt angle of the panel may be selected depending on the usual wind azimuth angle and may prove beneficial in lowering the temperature. Solar irradiance is usually thought of as being independent of the temperature, but in fact both parameters are correlated. With an increase in irradiance comes an increase in heat generation and, thus an increase in the temperature of the cell. On the other hand, irradiance also contributes positively to the output power of the solar cell, since the short circuit current will grow proportionally with the irradiance, which tends to dominate over the negative effect caused by the increase in the temperature of the cell.

IV. COMPUTATIONAL SIMULATIONS

In this section, several computational simulations were conducted to better understand the impact the temperature will have on solar cells. Always using the software *COMSOL Multiphysics*, the behavior of different types of solar cells with the temperature was simulated, and the temperature dependence of certain parameters, and the impact they will have on the solar cell, was studied. The computation simulations were done for both 1D and 2D models and comparisons were drawn.

A. 1D Solar Cells

Using the software *COMSOL Multiphysics*, 1D models of 4 different types of solar cells were created. For each type of solar cell, relevant data about the material such as the band gap, the electron affinity, and the effective density of states was inputted into the model. Furthermore, to achieve a greater accuracy, the complex refractive index of each material was also added to the computations. The cells were doped in a manner resembling real life cells and the photogeneration rate of the charge carriers was computed in the following way:

$$G(z) = \int_{0}^{\infty} \alpha(\lambda)\,(1 - R(\lambda))\phi(\lambda)e^{-\alpha(\lambda)z}d\lambda \qquad (6)$$

where $\alpha(\lambda)$ is the absorption coefficient, $R(\lambda)$ is the reflection coefficient, λ is the wavelength, $\phi(\lambda)$ is the photon generation ate, and z is the depth into the device from the surface. For the solar spectrum an approximation of the AM1.5 Global spectrum was used. In all 4 cases, solar cells with a diameter of 150 µm were designed, the geometry of which can be seen in figure 4.

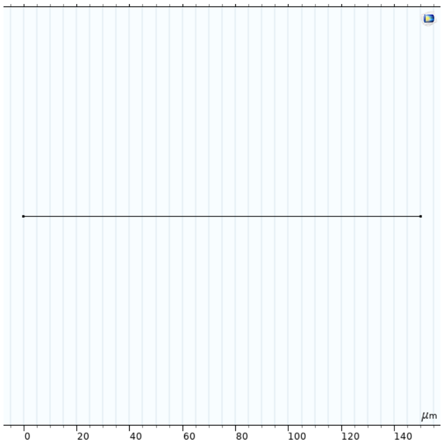

Figure 4 – *Geometry of the 1D Solar Cell*

For all the simulations, whenever a temperature coefficient is mentioned it is always expressed in %/ºC to allow for an easier comparison between the different types of cells and different experiments. The temperature coefficient also always refers to the lowest temperature measured for any particular experiment.

1) Silicon Solar Cell

Firstly, a simulation of the effect of different temperatures on a silicon solar cell was made. Four different temperatures of the material were tested, with the corresponding results being seen in Table 1. With an increase in the temperature there was a decrease in the V_{OC}, P_{MP}, and FF. For the V_{OC} and the P_{MP} the temperature coefficients were, respectively, approximately -0.37 %/°C and -0.47 %/°C. With regards to the I_{SC}, there was, as expected, a slight increase with the temperature, with a coefficient of about +0.005 %/°C, although the increase was less pronounced than is usual for silicon solar cells.

Table 1 – Solar cell parameters' data for the 1D silicon solar cell for 4 different temperatures

T (ºC)	$I_{SC}\ [mA]$	$V_{OC}\ [V]$	$P_{MP}\ [mW]$	FF
25	21.44	0.588	10.39	0.824
35	21.45	0.566	9.90	0.815
45	21.46	0.544	9.41	0.806
55	21.47	0.523	8.93	0.795

2) CIGS Solar Cell

Table 2 show the results of the simulation of a CIGS solar cell. Pure copper indium selenide (or $CuInSe_2$) was used as the semiconductor material of the cell, so more accurately, a simulation of a CIS cell was done. For the CIS solar cell, there was virtually no change in the I_{SC} with the variation in temperature. For the V_{OC} and the P_{MP}, there was a temperature coefficient of about -0.26 %/°C and -0.34 %/°C, respectively. The temperature coefficients show that in comparison with a silicon solar cell, the CIS cell is not as negatively affected by the temperature.

Table 2 – Solar cell parameters' data for the 1D CIGS solar cell for 4 different temperatures

T (ºC)	$I_{SC}\ [mA]$	$V_{OC}\ [V]$	$P_{MP}\ [mW]$	FF
25	31.51	0.586	15.14	0.820
35	31.51	0.571	14.62	0.813
45	31.51	0.555	14.08	0.805
55	31.51	0.540	13.58	0.798

3) CdTe Solar Cell

A simulation of a CdTe solar cell was next conducted. As can be seen in Table 3, with an increase in the temperature of a CdTe solar cell, there was a slight increase in the I_{SC} and a decrease in V_{OC}, P_{MP} and FF, which is all corroborated by the review of the literature that was done [6]. The V_{OC} and P_{MP} had a temperature coefficient of -0.18 %/°C and -0.23 %/°C, respectively. For the CdTe cell, it was found that, just like the literature indicated, the P_{MP} and consequently the efficiency is not as negatively affected by an increase in the temperature as is the case for silicon-based cells. However, the variation of the V_{OC} with the temperature was less pronounced than was expected, since the temperature coefficient of the V_{OC} was considerably smaller than in the silicon solar cell.

Table 3 – Solar cell parameters' data for the 1D CdTe solar cell for 4 different temperatures

T (ºC)	$I_{SC}\ [mA]$	$V_{OC}\ [V]$	$P_{MP}\ [mW]$	FF
25	25.71	0.992	22.42	0.879
35	25.71	0.974	21.90	0.875
45	25.72	0.956	21.39	0.870
55	25.72	0.938	20.87	0.865

4) Perovskite Solar Cell

Table 4 show the results of the simulation of the behavior of a Perovskite solar cell, using Methylammonium lead iodide ($CH_3NH_3PbI_3$) as the material of the semiconductor. For the Perovskite solar cell, an increase in the temperature led to a decrease in the value of the V_{OC} and P_{MP}, and a slight increase in the I_{SC}. The V_{OC} and P_{MP} had a temperature coefficient of -0.14 %/°C and -0.18 %/°C respectively, showing that the PSCs are, of all the cells simulated, the least negatively affected by the temperature.

Table 4 – Solar cell parameters' data for the 1D Perovskite solar cell for 4 different temperatures

T (ºC)	**$I_{SC}\ [mA]$**	**$V_{OC}\ [V]$**	**$P_{MP}\ [mW]$**	**FF**
25	15.11	1.093	14.60	0.884
35	15.11	1.078	14.34	0.880
45	15.12	1.063	14.08	0.876
55	15.12	1.048	13.82	0.872

The normalized P_{MP}, of all 4 solar cells can be seen in Figure 5, showcasing the different impact the temperature will have on the performance of the cells. The efficiency of the solar cells will decrease in much the same way as the P_{MP}, since neither the area of the cell nor the irradiance suffered any changes with the increase in temperature.

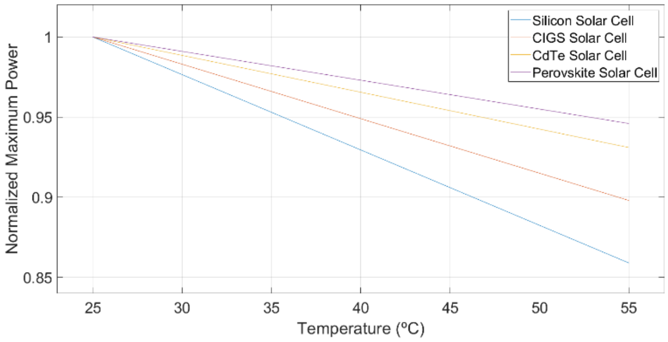

Figure 5 – *Normalized P_{MP} as a function of the temperature for the 4 solar cells*

B. The Temperature Dependence of the Band Gap

The band gap of the semiconductor material is an important parameter in the performance of the solar cell. The band gap is the energy difference between the conduction and the valence band, so, in other words, it is the minimum energy necessary to excite the electron and have it participate in the conduction process. As the temperature increases, the amplitude of atomic vibrations increase, which will subsequently increase the interatomic spacing and cause the interatomic bonds to be weakened, which means that less energy is needed to excite an electron into the conduction band and therefore there will be a decrease in the semiconductor's band gap. The relationship between some semiconductor's band gap and its temperature can be approximated by the Varshni equation, shown in the following expression:

$$E_g(T) = E_g(0) - \frac{\alpha\, T^2}{T + \beta} \tag{7}$$

where α and β are, material-dependent, fitting parameters and $E_g(0)$ is the bandgap observed at 0 K. Previously, when simulating the behavior of the 1D silicon solar cell, the value of the band gap inputted into the model equaled 1.121 eV which is the value of the bang gap of silicon measured at about 25 ºC. Now, in order to study the impact the change in band gap with the temperature will have on the performance of the silicon solar cell, computations were made for different temperatures using both the fixed 1.121 eV value and the more accurate calculated temperature dependent value. Tables 5, 6, and 7 show the results of the computations.

Table 5 – Solar cell's parameters for the 1D silicon solar cell for 2 different band gaps measured at 30º C

$E_g(30)[eV]$	**$I_{SC}\ [mA]$**	**$V_{OC}\ [V]$**	**$P_{MP}\ [mW]$**	**FF**
1.121	21.44	0.577	10.15	0.820
1.120	21.44	0.576	10.12	0.819

Table 6 – Solar cell's parameters for the 1D silicon solar cell for 2 different band gaps measured at 40º C

$E_g(40)[eV]$	**$I_{SC}\ [mA]$**	**$V_{OC}\ [V]$**	**$P_{MP}\ [mW]$**	**FF**
1.121	21.46	0.555	9.66	0.811
1.117	21.46	0.551	9.58	0.810

Table 7 – Solar cell's parameters for the 1D silicon solar cell for 2 different band gaps measured at 50º C

$E_g(50)[eV]$	**$I_{SC}\ [mA]$**	**$V_{OC}\ [V]$**	**$P_{MP}\ [mW]$**	**FF**
1.121	21.47	0.533	9.17	0.801
1.115	21.47	0.528	9.06	0.799

As can be seen by Tables 5,6 and 7, with a decrease in band gap comes a decrease in the V_{OC}, P_{MP}, and overall performance of the cell. The I_{SC} and FF, on the other hand, seem to be relatively unaffected. The decrease in V_{OC} can be explained by the effect the band gap will have on the intrinsic carrier concentration. With a decrease in the band gap, the n_i will increase which can be seen in expression (4). As was explained in section III, the increase in n_i will lead to an increase in the reverse saturation current which will cause a decrease in the V_{OC}. The decrease in band gap does not have as large an impact on the n_i as the effective density of states, but with higher temperatures the effect will progressively increase. With the, temperature dependent, band gap taken into consideration, more accurate values of the temperature coefficients of the V_{OC} and P_{MP} of the silicon solar cell can be computed. The V_{OC} has a temperature coefficient of about - 0.41 %/ºC and the P_{MP} has a temperature coefficient of about -0.52 %/ºC. For the I_{SC}, the decrease in the band gap of the semiconductor with an increase in temperature should theoretically lead to an increase in the value of the I_{SC} since a larger part of the solar spectrum can be absorbed by the cell which will subsequently cause an increase in the current generated. In terms of the computational simulations, however, it appears that the decrease in band gap with the temperatures that are usually reached by the solar cells does not have a great effect on the I_{SC}.

C. The Temperature Dependence of the Refractive Index

The complex refractive index is defined in the following way:

$$\bar{n} = n + jk \tag{8}$$

where n is the refractive index and refers to the phase velocity of light in the material and the k is the extinction index which relates to the way light is attenuated in the medium. The extinction index is directly responsible for the absorption of light into the medium and it is correlated with the absorption coefficient. Both the real and the imaginary parts of the complex refractive index are directly affected by the temperature of the material. For the case of silicon, for temperatures that solar cells can realistically be expected to reach, with an increase in the temperature there will be an increase in the refraction and extinction index, regardless of the wavelength of the solar spectrum. For all wavelengths above 450 nm and below 1100 nm, and for all temperatures above 298 K, the real part of the complex refractive index, n, can be expressed as a function of both the wavelength of the radiation and the temperature.

$$n(\lambda, T) = n_0(\lambda) + a_n(\lambda)(T - T_{0n}) \tag{9}$$

In the above expression, T_{0n} is the reference temperature which equals $25°C$, $n_0(\lambda)$ is the reference refractive index taken at $25°C$ and $a_n(\lambda)$ is a fitted polynomial function. For the case of the extinction index, k, and for wavelengths of sunlight between 450 nm and 840 nm, its temperature dependence can be expressed as an exponential function:

$$k(\lambda, T) = k_0(\lambda) e^{T/T_0(\lambda)} \tag{10}$$

where $k_0(\lambda)$ and $T_0(\lambda)$ are both fitted functions. For wavelengths between 840 nm and 1100 nm, an extrapolation of the values of the extinction index was made. Previously, when simulating the behavior of the 1D silicon solar cell, the complex refractive index remained the same for all the temperatures tested. In that case, the complex refractive index had been taken from a refractive index library and referred to silicon at 25 ºC. Now, to observe the effects of the, temperature-dependent, complex refractive index on the performance of the silicon solar cell, several tests were conducted on the 1D cell, using both the original and the, more accurate, adjusted complex refractive index. Tables 8, 9 and 10 show the results of the computations.

Table 8 - Solar cell's parameters for the 1D silicon solar cell for at 30ºC with the original and adjusted complex refractive index

Refractive Index	I_{SC} $[mA]$	V_{OC} $[V]$	P_{MP} $[mW]$	FF
Original	22.21	0.577	10.50	0.819
Adjusted	22.25	0.577	10.53	0.820

Table 9 - Solar cell's parameters for the 1D silicon solar cell for at 40ºC with the original and adjusted complex refractive index

Refractive Index	I_{SC} $[mA]$	V_{OC} $[V]$	P_{MP} $[mW]$	FF
Original	22.22	0.555	10.00	0.811
Adjusted	22.31	0.555	10.04	0.811

Table 10 - Solar cell's parameters for the 1D silicon solar cell for at 50ºC with the original and adjusted complex refractive index

Refractive Index	I_{SC} $[mA]$	V_{OC} $[V]$	P_{MP} $[mW]$	FF
Original	22.23	0.533	9.50	0.802
Adjusted	22.37	0.534	9.56	0.800

As can be seen by Tables 8,9 and 10, when the adjusted complex refractive index is considered, the I_{SC} will grow considerably more, now having a temperature coefficient of about +0.03 %/°C which is much closer to what is usually observed in real life cells. The change in the I_{SC} can perhaps be best explained due to the change in the generation rate of the charge carriers. With an increase in temperature comes an increase in the value of the extinction index which will subsequently cause an increase in the absorption coefficient. An increase in the absorption coefficient means that the semiconductor will more readily absorb photons which will subsequently cause an increase in the generation of charge carriers, which will lead to an increase in the I_{SC}, since it is known that the I_{SC} is strongly dependent on the generation rate. At the same time, the adjusted complex refractive index seems to have had almost no effect in the V_{OC} or FF of the cell. The slight increase in the P_{MP}, when the adjusted complex refractive index is taken into consideration, is expected since, for reasons stated above, there will be an increase in the current produced by the cell. It is worthy of note that, for both the original and the adjusted complex refractive index, no wavelengths lower than 450 nm were considered in the computational simulations since, for those wavelengths, their exact dependence on the temperature could not be found in the revision of the literature. However, since it is still known that, with an increase in temperature, the real and imaginary part of the complex refractive index will grow, this in no way affects what was previously concluded.

D. 2D Silicon Solar Cell

A 2D model of a silicon solar cell was designed and implemented on the software *COMSOL Multiphysics*. By using a 2D model, a more accurate representation of the behavior of the silicon a solar cell can be studied since now the width of the cell is considered in the computations. The geometry of the 2D cell can be seen in Figure 6.

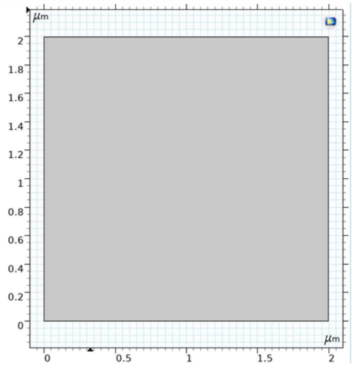

Figure 6 – *Geometry of the 2D Silicon Solar Cell*

In order to compare the behavior of the 2D cell with the temperature, with the previously used 1D cell, several tests were conducted. First, the 2D cell was tested at 4 different uniform temperatures with the corresponding results being seen in table 11.

Table 11 – Solar cell parameters' data for the 2D silicon solar cell for 4 different temperatures

T (ºC)	$I_{SC}\ [mA]$	$V_{OC}\ [V]$	$P_{MP}\ [mW]$	FF
25	9.74	0.480	3.58	0.766
35	9.72	0.455	3.34	0.755
45	9.71	0.430	3.11	0.745
55	9.69	0.404	2.87	0.733

As can be seen in the previous table, with an increase in temperature, several changes occurred in the behavior of the silicon solar cell. The V_{OC} and P_{MP} decreased with the temperature, which is expected, although the decrease was more pronounced than it was in the 1D model. The V_{OC} had a temperature coefficient of around -0.52 %/ºC and the P_{MP} had a temperature coefficient of about -0.67 %/ºC. The I_{SC} experienced a slight decrease, which is contrary to what was observed on the 1D model, and in most commercial silicon solar cells. The temperature coefficient was approximately -0.02 %/ºC. The decrease in the value of the I_{SC} can perhaps be best explained by the higher degrees of recombination that occur in the 2D model.

1) The Temperature Dependence of the Band Gap

Just like in the 1D model, a study of the impact the temperature dependent band gap will have on the cell's performance was conducted. Tables 12, 13 and 14 show the results of the computations.

Table 12 – Solar cell's parameters for the 2D silicon solar cell for 2 different band gaps measured at 30º C

$E_g(30)[eV]$	$I_{SC}\ [mA]$	$V_{OC}\ [V]$	$P_{MP}\ [mW]$	FF
1.121	9.73	0.467	3.46	0.761
1.120	9.73	0.466	3.45	0.761

Table 13 – Solar cell's parameters for the 2D silicon solar cell for 2 different band gaps measured at 40º C

$E_g(40)[eV]$	$I_{SC}\ [mA]$	$V_{OC}\ [V]$	$P_{MP}\ [mW]$	FF
1.121	9.72	0.442	3.23	0.752
1.117	9.71	0.438	3.19	0.750

Table 14 – Solar cell's parameters for the 2D silicon solar cell for 2 different band gaps measured at 50º C

$E_g(50)[eV]$	$I_{SC}\ [mA]$	$V_{OC}\ [V]$	$P_{MP}\ [mW]$	FF
1.121	9.70	0.417	2.99	0.739
1.115	9.70	0.411	2.94	0.737

In the 2D cell, the temperature dependent band gap impacted the solar cell in much of the same way that it did in the 1D model. When the more accurate band gap is inputted into the model, there will be a decrease in the V_{OC} and P_{MP} of the cell, which is caused by the, previously discussed, changes in the intrinsic carrier concentration. The I_{SC} and the FF were, once again, little affected by the change in band gap. The more accurate temperature coefficient of the V_{OC} was - 0.58 %/ºC and for the P_{MP} it was approximately - 0.72 %/ºC. The change in the temperature coefficients was slightly more pronounced for the V_{OC} but virtually the same for the P_{MP}.

2) The Temperature Dependence of the Refractive Index

Next, the temperature dependent complex refractive index was inputted into the model, and comparison were made with the complex refractive index taken at 25 ºC. Tables 15, 16 and 17 show the result of the computations.

Table 15 - Solar cell's parameters for the 2D silicon solar cell for at 30ºC with the original and adjusted complex refractive index

Refractive Index	$I_{SC}\ [mA]$	$V_{OC}\ [V]$	$P_{MP}\ [mW]$	FF
Original	8.25	0.463	2.91	0.762
Adjusted	8.43	0.463	2.97	0.761

Table 16 - Solar cell's parameters for the 2D silicon solar cell for at 40ºC with the original and adjusted complex refractive index

Refractive Index	$I_{SC}\ [mA]$	$V_{OC}\ [V]$	$P_{MP}\ [mW]$	FF
Original	8.24	0.438	2.70	0.748
Adjusted	8.53	0.439	2.80	0.748

Table 17 - Solar cell's parameters for the 2D silicon solar cell for at 50ºC with the original and adjusted complex refractive index

Refractive Index	$I_{SC}\ [mA]$	$V_{OC}\ [V]$	$P_{MP}\ [mW]$	FF
Original	8.23	0.412	2.50	0.737
Adjusted	8.64	0.414	2.64	0.738

When the adjusted complex refractive index is taken into consideration, the I_{SC}, now, experiences a growth with the temperature, which aligns with the usual behavior of silicon solar cells. The reasons for this, as was explained before, have to do with the absorption coefficient and the generation of charge carriers. The temperature coefficient of the I_{SC} is now positive, instead of negative, being approximately +0.11 %/ºC which is higher than the traditionally I_{SC} coefficient for silicon cells. The reason why the values of the I_{SC} are overall lower than they were when the 2D solar cell was first simulated, is because not all wavelengths of the incident sunlight are being considered. This does not, however, affect any of the general conclusions that were drawn about the behavior of the I_{SC} with the extinction index. Unlike the 1D model, the V_{OC} is slightly higher if the adjusted complex refractive index is used, rather than the original, showing that the more accurate temperature coefficient of the V_{OC} is not quite as pronounced as was previously reported. The increase in the maximum power is easily explained by the growth in the short circuit current and open circuit voltage.

V. COOLING METHODS

Having already established the negative impact that the temperature will have on the performance of photovoltaic systems, some solutions are now proposed, intended for the reduction of this negative effect. A review of the literature was conducted, where several ways of using the unnecessary heat generated in the panel, or of cooling the photovoltaic system were analyzed and studied.

A. Photovoltaic Thermal Collector

Photovoltaic/thermal (or PV/T) collectors are units comprised of a photovoltaic system, which will convert sunlight into electricity, and a solar thermal collector which will convert sunlight into thermal energy. By using a PV/T collector it is possible not only to cool the photovoltaic system, but also to extract the unnecessary heat produced by the PV system, which will then be converted into useful energy. A typical PV/T collector consists of a PV module which is installed on top of a heat absorber on top of an insulator. The waste heat produced by the PV system will be transferred to a heat transfer fluid. The heat transfer fluid can be a gas or a liquid which is responsible for cooling the PV module and transporting and storing the thermal energy. Depending on the heat transfer fluid used, the PV/T collectors can be broadly divided into two following categories: PV/T air collector and PV/T liquid collector.

PV/T air collectors have several advantages, the main one being that they are relatively cheap and easy to manufacture. They also do not require any thermal collecting materials attached to the PV system. On the other hand, since the air has a low heat capacity and low heat conductivity, the heat transfer will not be very pronounced and consequently the PV/T air collectors will not have a very high efficiency.

PV/T liquid collectors are more efficient than PV/T air collectors, since the liquid used (typically water) has a higher heat conductivity and heat capacity, resulting in a higher volume of heat transfer and consequently an increase in the efficiency of the system. Some disadvantages include higher manufacturing cost and maintenance. Unlike PV/T air collectors, however, in PV/T liquid collectors it is possible for the liquid to boil or freeze which will impact the efficiency of the system or for there to be leakage of the fluid which will cause damage to the collector [15].

B. Phase Change Material

A method that may be used to cool the photovoltaic system, and thereby increase its efficiency, is the installation of phase change materials (PCMs) on the back of the solar panels. PCMs are substances that undergo a reversible transition of phase (usually between the solid and liquid states), while absorbing or rejecting heat in the process. PCMs have the advantage of having several times more heat capacity than water or air based systems and are able to store heat which can subsequently be used for other purposes [16]. They also have the added advantage of being able to delay the temperature rise in the photovoltaic system without any electricity consumption or requiring maintenance. Some of their disadvantages include a large initial investment, corrosiveness, and the fact that they tend to perform better in hot climatic conditions [17]. Figure 7 shows a typical PV module with a PCM layer attached to the backside of the panel.

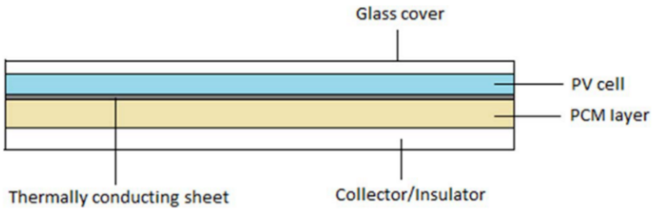

Figure 7 – *Cross-section of a PV module with a PCM layer attached at the rear [16]*

C. Water Immersion

A method that may be employed to cool the photovoltaic system is the immersion of the solar panel in a body of water. This technique has some advantages as well as some drawbacks. Aside from the natural effects that the cooling will have on the efficiency of the PV system, immersing the panel in water will also cause a reduction in the light reflection which will prove beneficial for the efficiency [18]. Immersing the solar panel in water is an efficient and environment-friendly process, although consideration also as to be taken, since the complexity and cost of this cooling technique can be quite high. The efficiency of the submerged solar panel will also not be as high during cloudy days and the prolonged exposure of the panel to ionized water will eventually decrease its maximum efficiency [17].

D. Water Spraying

A similar method to the water immersion, is the cooling of the solar panel by the continuous flow of water over the front surface of the panel. This technique will not only reduce the temperature of the panel, but also, due to the refractive index of the water, the refection losses of the panel [19]. Unlike the water immersion method, to implement this method, a pump is necessary, to transport the water from a tank that is located below the photovoltaic module into another that is located on top of the PV system. This continuing water flow has the added advantage of, while keeping the solar panel cool, also making it clean from dust and other particles that negatively affect the performance of the panel.

Also, like the water immersion method, water spraying of the solar panel is not the most overall efficient technique since the excess heat generated by the panel, and cooled by the water, will not be used for other applications. This cooling method will also require a higher degree of maintenance and a higher cost due to the pumping power that will be necessary to ensure the cooling of the panel.

E. Transparent Coating

The front surface of the PV module may be covered by a visibly transparent photonic crystal thermal blackbody, where the main constituent of the photonic material will be silica (SiO_2). When this blackbody is placed on top of the solar panel, it will reflect heat generated by the panel, while, at the same time, not negatively affecting the sunlight absorption [20]. Unlike photovoltaic thermal collectors or PCMs however, this cooling method does not take advantage of the heat generated, although the use of a transparent blackbody over the panel has the advantage of being economically feasible and not requiring any additional space.

F. Thermoelectric Cooling

In order to cool the photovoltaic system, it is possible to attach a thermoelectric cooling (TEC) module to the rear of the panel. A TEC module is an energy converter made up of two different semiconducting thermoelements which are wired electrically in series and thermally in parallel. When a voltage is applied to the TEC module, an electric current will flow through the device which will cause a transfer of heat from one side of the TEC module to the other side, so that one side of the TEC module will be cooler while the other side will be hotter. The “hotter” side will be connected to a heat sink which will dissipate the thermal energy into the environment. Using a thermoelectric cooler to decrease the temperature of a photovoltaic system has some drawbacks, the main ones being the fact that TEC modules will consume more power than most cooling systems, while at the same time, having a low conversion efficiency rate. One the other hand, TEC modules have the advantage of being more economical than other cooling systems. They also have the added benefit of being noiseless in operation, having no moving mechanical parts, having a long working life and requiring little maintenance [21]. A diagram showcasing the operation of a standard thermoelectric module is shown in figure 8.

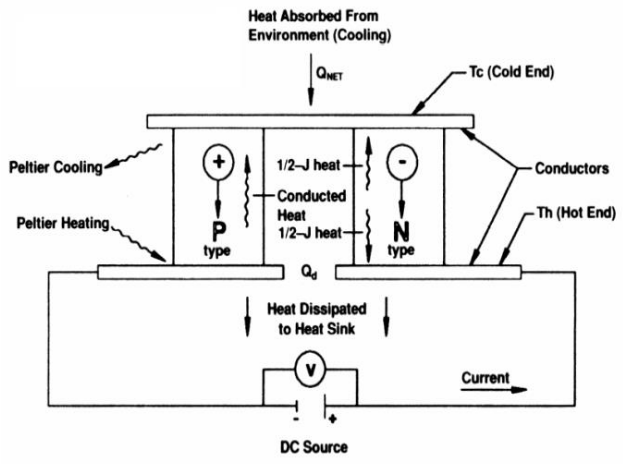

Figure 8 – *Working of Thermoelectric Module* [22]

VI. CONCLUSION

The main objective of this paper was the study of the impact the temperature will have on the performance of solar cells.

In terms of the theoretical analysis that was done, it was found that the temperature will mainly affect the performance of solar cells due to the impact the temperature will have on the effective density of states and the band gap of the semiconductor, which will subsequently increase the intrinsic carrier concentration. This increase will be responsible for a decrease in the V_{OC} which is the parameter most affected by the temperature and which will be primarily responsible for the decrease in the P_{MP} and efficiency of the cell.

Using the software *COMSOL Multiphysics*, and resorting to 1D models, comparisons between the performance of different solar cells in function of the temperature were made. It was found that perovskite solar cells are the least negatively affected by an increase in temperature, performing better than CdTe and CIGS cells. Silicon solar cells are, of all the cells tested, the ones who perform worse with an increase in temperature.

For the 1D silicon solar cell model, it was found that the decrease the band gap suffers with the temperature, mainly affects the V_{OC} , while the increase the extinction index undergoes with the temperature will cause an increase in the I_{SC} which contributes slightly to a better performance by the cell.

By using a 2D model of the silicon solar cell it was intended to more accurately represent the behavior of a real cell. The simulations done with this model show similar effects of the temperature on cell’s parameters, with the only differences being slightly more pronounced decreases in the V_{OC} and P_{MP} and a slight decrease of the I_{SC} with the temperature instead of a slight increase. When it comes to the effect of the band gap and the complex refractive index, their impact was much the same as it was in the 1D model.

The review of the cooling systems that may be employed to lower the temperature of the photovoltaic system show that the choice of the cooling system will depend on whether the customer wishes to make use of the excess heat, the budget of the customer and the location of the installation of the PV module.

The principal advantage of doing computational simulations to study the behavior of solar cells was that it was possible to completely isolate the impact the temperature will have, by keeping other external factors, such as the irradiance, constant. Since this will not be the case in commercial cells further studies into the performance of cell under real conditions are recommended to better understand how they will be affected by the temperature. Also recommended is further studies into the band gap, complex refractive indexes, and effective density of states of semiconductors other than silicon, since there seems to be a scarcity of published literature on the subject.

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