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Analysis of the effects of non-uniform irradiance and temperature on a CPV dense array output power cooled by microchannels and microfluidic cells.

MASTER THESIS

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3. Abstract

This project presents an electrical analysis of CPV dense array under different temperature and irradiance conditions and for different electrical configurations. The classical cooling system used for CPV is microchannels but in the European Project Streams a new cooling system called microfluidic cells is being developed. A mathematical model is used to reproduce the behaviour of a photovoltaic cell. It will be calibrated for temperature variations using the information given in the datasheet so the electrical power losses can be studied. Then, an irradiance distribution will be chosen and used to calculate the temperature distributions for microchannels and microfluidic cells cooling systems. Finally, different electrical configurations will be tested for the temperature and irradiance distributions to study the effect they have on the electrical power output.

4. Introduction

Installing systems of electric power generation from solar energy usually involves a considerable economic investment due to the cost of the semiconductor materials of which the cells are formed and the costs derived from the large extensions to be occupied if some power is desired.

To reduce this type of costs, solar concentrators are used. In them, lenses, curved mirrors and other types of optics are used to concentrate a large amount of solar radiation in a small area of photovoltaic cells [3,5]. They are known as CPV, from English Concentrator Photovoltaics. In this way multi-junction photovoltaic cells can be installed, which are more expensive but more efficient than conventional ones.

It is known that in these systems, differences in the working conditions in the photovoltaic cells, negatively affect the production of energy. The non-uniformity in radiation [1,8,9] and temperature, the model of the different photovoltaic cells of a matrix, shadows or even some damage, produce losses in the electrical production.

This is known as "Mismatch effect" that leads to significant electrical losses [1] and even the creation of a hot spot in any of the cells, which can lead to the destruction of the same.

The impact on the power losses depend on:

- The operating point of the CPV array.
- The circuit configuration.
- Parameters which are different from other solar cells.

In this project the effects of non-uniform irradiance and temperature on different electrical configurations of a dense CPV array will be studied for microchannels and microfluidic cells cooling systems.

5. Background

An article that studies the phenomena mentioned in the introduction is Fei-Lu and Kok-Keong Chong's "A Systematic Method of Interconnection Optimization for Dense-Array Concentrator Photovoltaic System" where the effects of non-uniformity of radiation on a dense matrix of 48 photovoltaic cells and connecting them in different configurations to see how they behave. In this case the temperature of all cells is set. A study is done first in Matlab and then a prototype is built to check the results. The relevant data show that the configuration where all the cells are connected in series is the most affected by non-uniformity and that the combinations of cells in series and in parallel give better results.

In “Numerical modelling and thermal optimization of a microfluidic cooling panel for electronics” microfluidic cells are studied as a cooling system that has better unifying capacities than the microchannels cooling system.

6. Project justification

The improvement of photovoltaic technology and in this case of concentration is an extremely important issue in order to move towards a future free from fossil fuel-dependent energies and where renewable energy sources supply most of the energy consumed.

Nowadays, many efforts are being made to make solar energy more competitive, and that is why it is necessary to increase the efficiency of the systems, to understand why the mismatch losses happen and know how to reduce them.

The aim of this project is to study the electrical effects of non-uniform temperature distribution on a CPV dense array in combination of a non-uniform irradiance distribution. In addition, it is also considered important to carry out the study for high solar concentration (1000 suns or more).

7. Objectives

The project wants to provide knowledge of how CPV dense arrays behave in conditions of non-uniform temperature and irradiance. The main project objectives are:

- Study and compare the effects of microchannels and microfluidic cells cooling system on a CPV dense array output power.
- Calibrate and use a mathematical model to approximate the behaviour of a photovoltaic cell.
- Analyse the electrical effects of non-uniform temperature and irradiance on a dense matrix of photovoltaic cells.
- Understand how the series, parallel and mixed connections are affected by mismatch losses and discern for every situation of non-uniformity the best way to connect the cells.
- Study the implementation of power supplies to groups of PV cells on a dense array in order to increase power output of the system.

8. Methodology

8.1. Work plan

1. Select a PV cell with which all the electrical studies will be done.
2. Adjust and calibrate the reduced mathematical model so it can represent the information found in the cell datasheet.
3. Validate the calibrated model with the article "A Systematic Method of Interconnection Optimization for Dense-Array Concentrator Photovoltaic System" Fei-Lu and Kok-Keong Chong.
4. Select a non-uniform and a uniform irradiance distribution with which the thermal studies will be done.
5. Apply the irradiance distributions to microchannels and microfluidic cells cooling systems to obtain the temperature distributions with which the electrical studies will be done.
6. Selection of electrical configurations for the CPV dense array.
7. Calculation for all the electrical connections the I-V curve and the maximum power they can produce.
8. Analysis of the results.

8.2. Chosen PV cell

In order to realise the electrical study the model "C4MJ Metamorphic Fourth Generation CPV Technology" created by SPECTROLAB is chosen.

It is a triple-union cell made of GalnP (1,82 eV) / GalnAs (1,33 eV) / Ge (0,66 eV).

Multi-junction solar cells are solar cells with multiple p-n junctions made of different semiconductor materials. Each material's p-n junction will produce electric current in response to different wavelengths of light.

The use of multiple semiconducting materials allows the absorbance of a broader range of wavelengths improving the cell's sunlight to electrical energy conversion efficiency.

The "C4MJ" claims to have a 40% efficiency.

The characteristics (at 25ºC) of the 1.0 * 1.0 cm^2 PV cells are described in Figure 1.

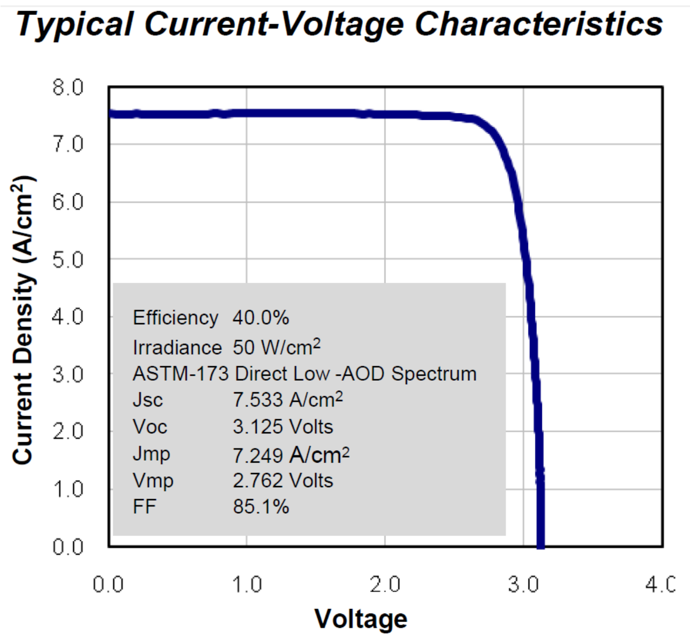

Figure 1. SPECTROLAB triple-union cell characteristics.

The cell datasheet is presented in Annex 7.

8.3. Theoretical basis

The PV cell characteristic IV curve has been used to calibrate the reduced model [8,9] used for the assessment of the PV cell power output under different irradiation and temperature conditions.

The reduced model is used for simple PV cells but in this project the model will be adjusted for a triple-union cell so what was known as the band gap, in this project will be known as the equivalent band gap. The model can be defined by the following equations:

$$I = I_L \cdot \frac{C}{C_0} - I_0 \cdot \left[e^{\frac{V}{V_T}} - 1\right] \quad (1)$$

and its reverse equation:

$$V = V_T \cdot \ln\left(\frac{I_L}{I_0} - \frac{I}{I_0} + 1\right) \qquad (2)$$

Where V and I are the potential and the current of the of the PV cell, respectively. C_0 is the reference solar concentration (500 suns) and I_0 is the cell temperature (T) dependence of the equivalent reverse diode current:

$$I_0 = I_0' \cdot T^3 \cdot e^{\frac{C_1}{K_B \cdot T}} \qquad (3)$$

Where K_B is the Bolztman constant, T is the temperature in Kelvin, $I_0{}'$ is the reverse current factor, independent of the temperature, C_1 is the equivalent band gap and the thermal voltage V_T, defined as:

$$V_T = \frac{K_B \cdot T \cdot n}{e^-} \qquad (4)$$

Where n is the ideality reduced factor and e^- is the electron charge.

8.4. Reduced model calibration

8.4.1. I-V calibration

Both model equation and reverse equation are useful because the electrical study needs the model equation for parallel cells and the reverse equation for series cells.

The I-V curve obtained from the datasheet was digitalized in order to compare the future results from the calibration.

With the model equation, the reverse equation and the digitalized curve, two errors between the calculated curves and the digitalized one are found.

There are 4 parameters in the model that can be changed:

- Short circuit current, I_L (A).
- Ideality reduced factor, n.
- Reverse current factor, $I_0{}'$ (A/K^3).
- The equivalent band gap, C_1 (J).

The short circuit current I_L has been given in the cell datasheet.

The I-V calibration has been done by changing the ideality reduced factor n and the reverse current factor I_0'. It has been done in Excel using the tool "Solver" by minimizing the error between the calculated and the digitalized values. When the calibration was done only for the model equation, the parameters obtained made the reverse equation adjust incorrectly and the same happened the other way around. So it was necessary to do the calibration for the two errors at the same time.

In the calibration with "Solver" more importance was given to the values located near the maximum power voltage of the I-V curve because the I-V curve slope is so small for low voltages that errors in the digitalization were easily made.

The parameters found are:

- Ideality reduced factor, $\boldsymbol{n = 4.123}$
- Reverse current factor, $\boldsymbol{I_0' = 0.11104}$ **(A/K^3)**.

In figures 2 and 3 the model equation error and the reverse equation error are presented:

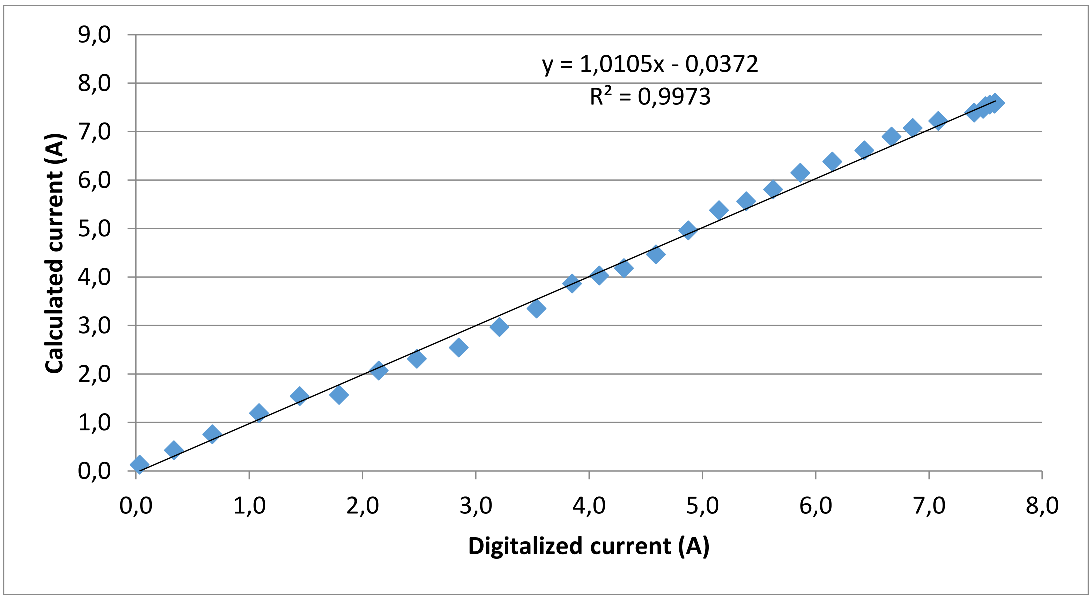

Figure 2. Model equation error.

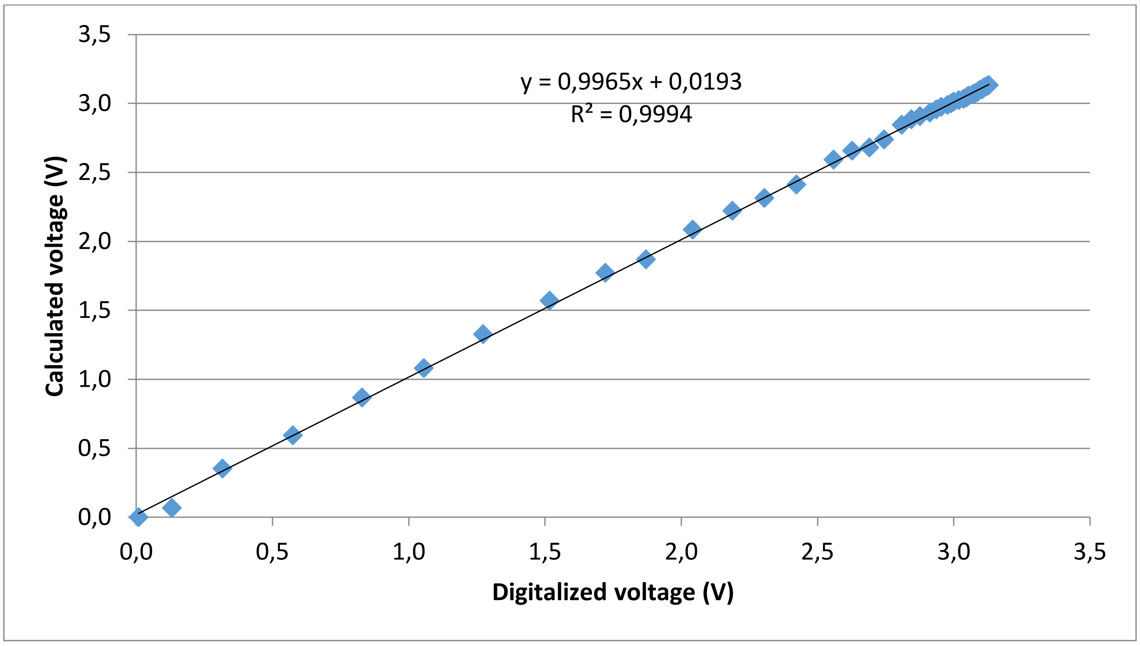

Figure 3. Reverse equation error.

As it can be seen both equations have a high coefficient of determination, this means that the parameters found in the I-V calibration make both model and reverse equations adjust the digitalized values from the datasheet correctly.

The comparison of the digitalized curve and the two calculated curves is shown in figure 4:

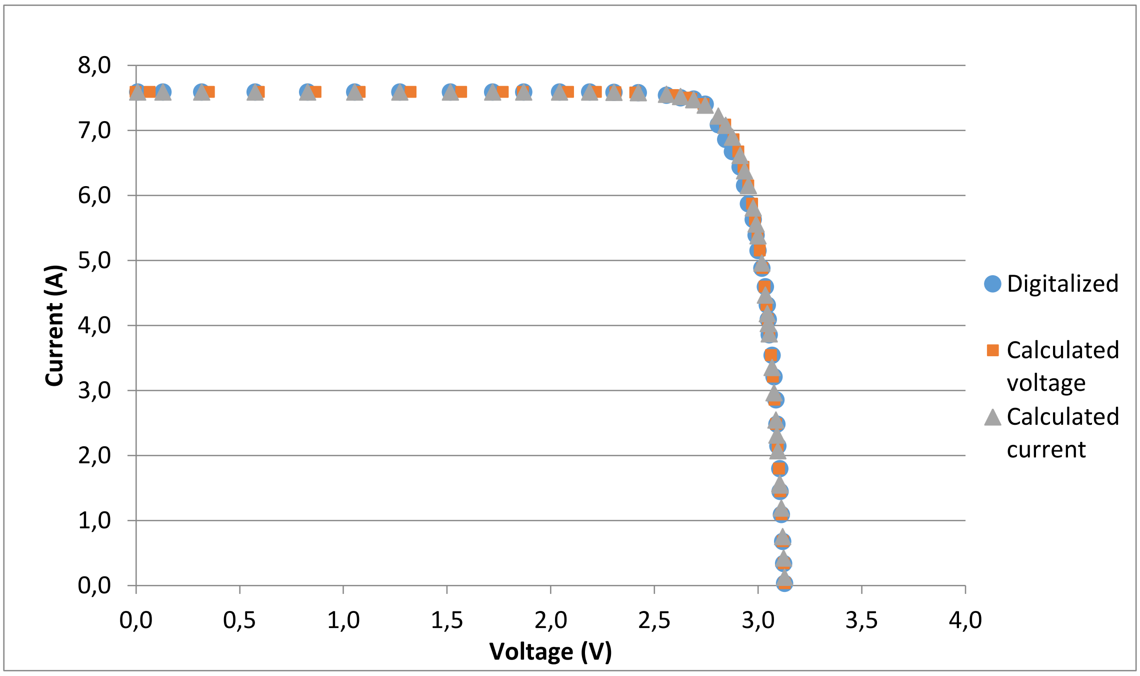

Figure 4. Comparison of the digitalized curve (blue dots), the one obtained from the model (in grey triangles) and the one obtained from the reverse model (in orange squares) for 25°C and 500 suns.

The model equation and the reverse equation have been correctly calibrated so they are adjusted to the digitalized curve obtained from the cell datasheet.

8.4.2. Temperature calibration of the I-V curve

The temperature calibration is mainly done by changing the equivalent bandgap of the 3 semiconductor materials that form the cell.

In the datasheet it can be found how the short circuit current J_{SC}, the open circuit voltage V_{OC}, and the maximum power voltage V_{mp}, change with increasing temperature. It can be seen in table 1:

Table 1. Datasheet information used for the temperature calibration.

J_{sc}	$\frac{8.2\frac{\mu A}{cm^2}}{°C}$
V_{OC}	$-6.4\frac{mV}{°C}$
V_{mp}	$-6.7\frac{mV}{°C}$

After using the solver program to minimize the error by changing the equivalent bandgap, the equivalent bandgap found is:

$$\boldsymbol{C_1 = 1.1397\,J}$$

In figures 5,6 and 7 the differences between the datasheet information and the calculated one are shown

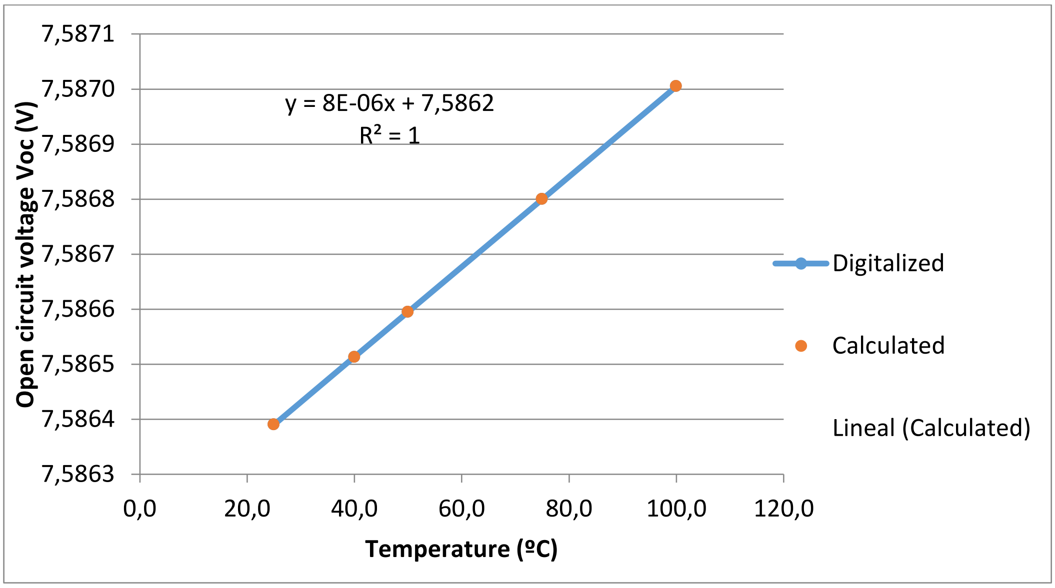

Figure 5. Comparison between the Jsc given in the datasheet and the calculated one after the temperature calibration.

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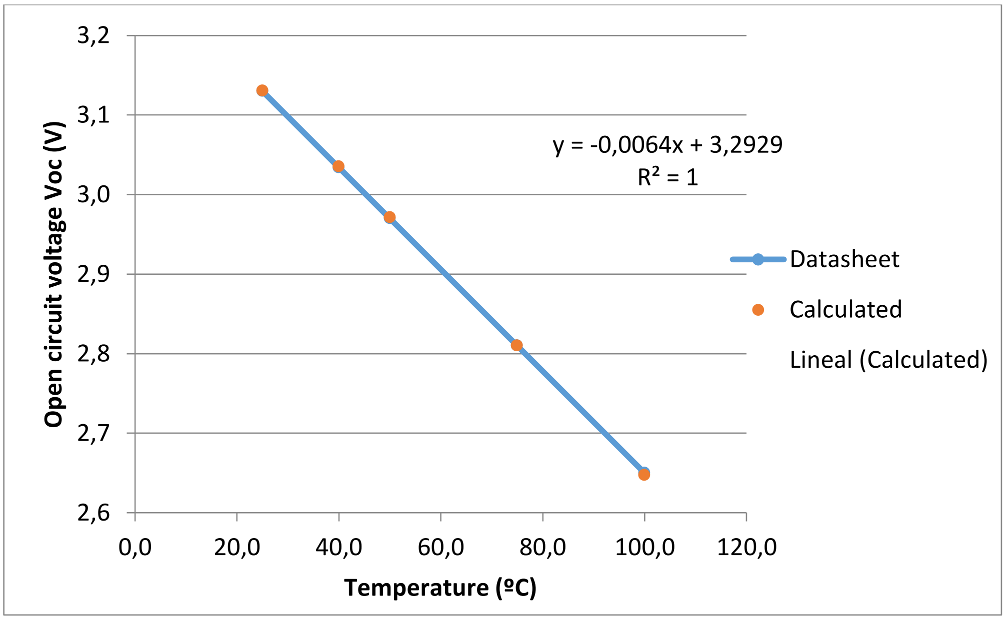

Figure 6. Comparison between the Voc given in the datasheet and the calculated one after the temperature calibration.

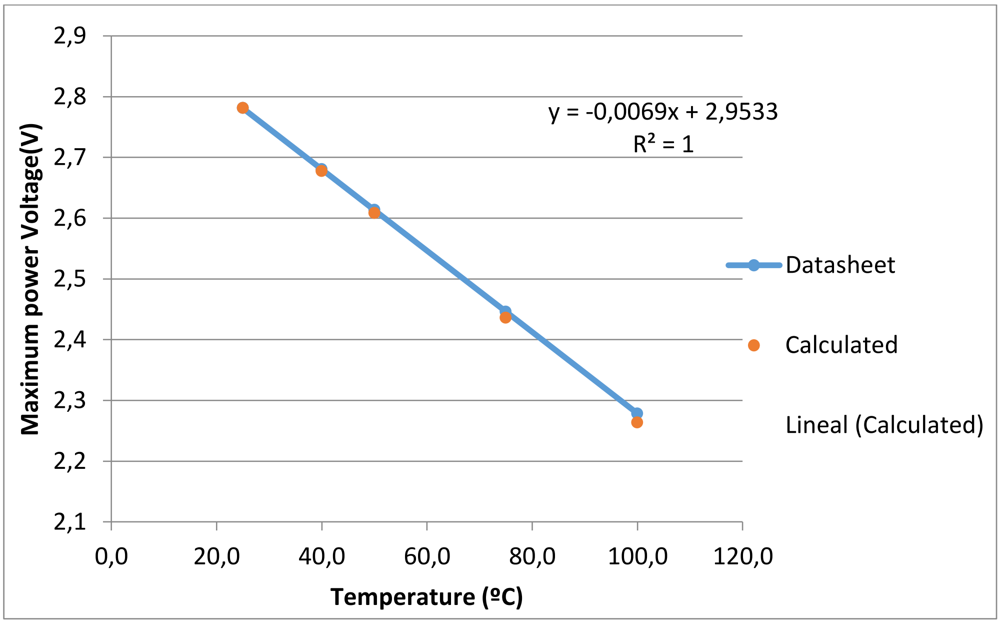

Figure 7. Comparison between the Vmp given in the datasheet and the calculated one after the temperature calibration.

The temperature calibration has been correctly done because the coefficient of determination is so small that Excel approximates it to 1.

The obtained values after the calibration are presented in Table 2:

Table 2. Calculated values after the calibration of the mathematical model.

Description	Symbol	Value
Short-circuit current	I_L	7.533 A
Reverse current factor	$I_0{}'$	0.11104 A/K^3
Equivalent bandgap	C_1	1.1397J
Boltzman constant	K_B	1.38065·10-23 J/K
Elementary charge	e^-	1.602·10-19 C
Ideality reduced factor	n	4.123

The I-V curves calculated for different temperatures with the calibrated model are presented in figure 8:

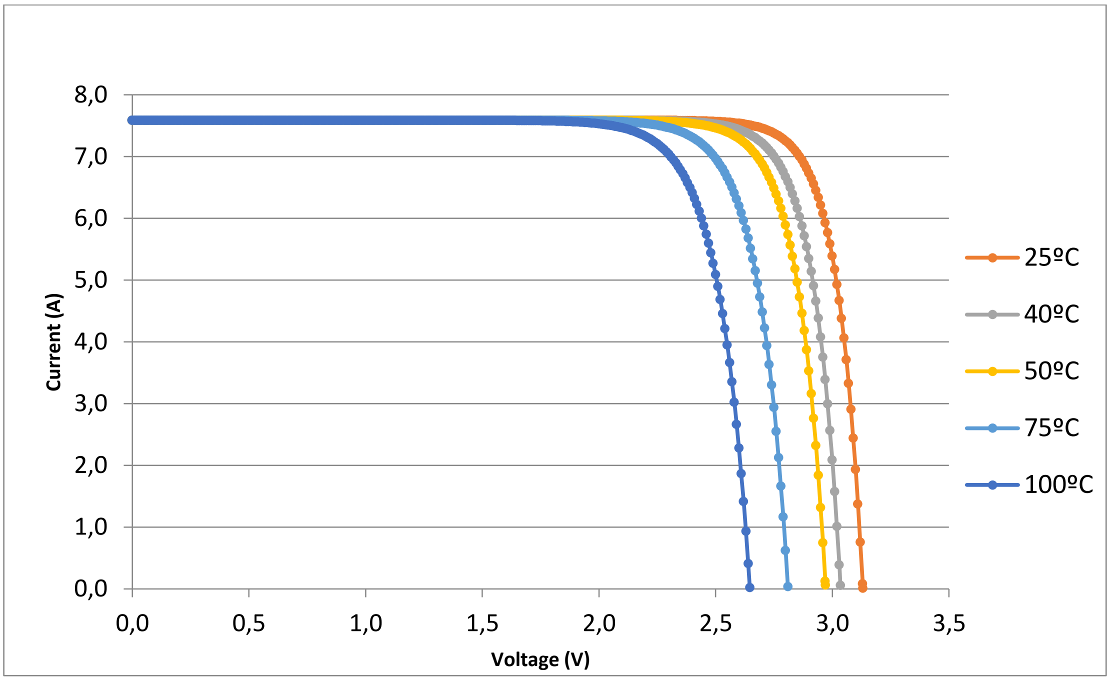

Figure 8. I-V curve for different temperatures using the calibrated model at 500 suns.

More information of the calibration process is presented in Annex 1.

8.5. Mathematical model validation

Once the model is completely calibrated, it is compared with the results of a scientific article to see if it is well-adjusted.

The article used is “A Systematic Method of Interconnection Optimization for Dense-Array Concentrator Photovoltaic System” Fei-Lu and Kok-Keong Chong. The authors analyse the effect of a non-uniform irradiance distribution in a dense-array CPV receiver formed with 48 multi-junction cells. The irradiance distribution is presented if figure 9:

Figure 9. Article's irradiance distribution (suns).

The authors of the article fix the temperature of all the cells at 55ºC and calculate the maximum power generated for different electrical configurations.

48x1, 12x4 and 6x8 configurations were studied in the article and have been tested with the calibrated mathematical model. Each PV cell had its model equation introduced in Excel and using “Solver” the electrical power was maximized in order to find the maximum power of the CPV dense array. The results are presented in figure 10:

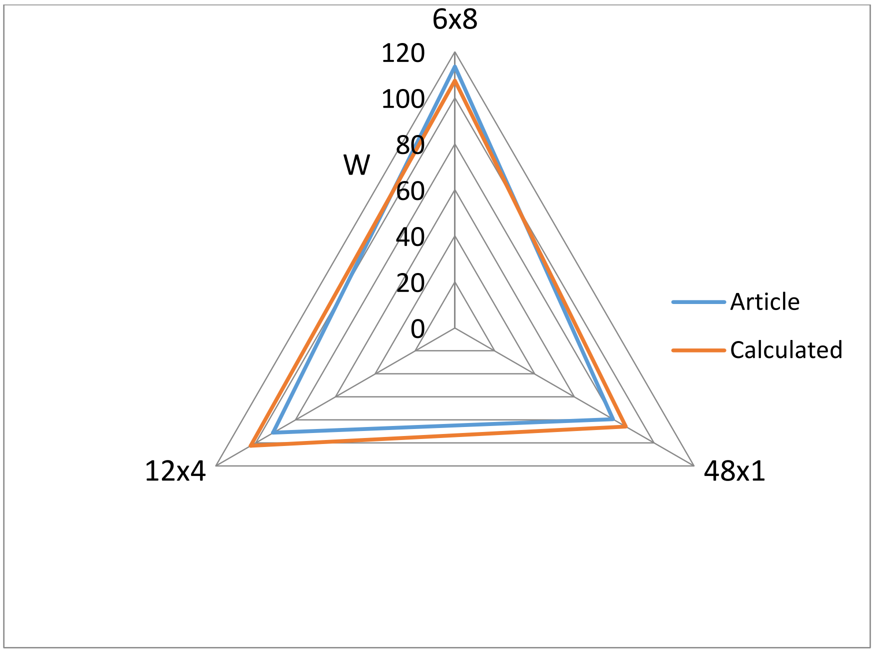

Figure 10. Comparison between the article’s results and the ones obtained after the calibration.

As it can be seen in figure 10 the electrical power values of the article and the calculated ones for each configuration are similar. The differences may be due to differences in the PV cell.

It can be affirmed that calibrated mathematical model is well-adjusted.

8.6. High concentration irradiance distribution

Once the calibrated model has been validated, it is necessary to choose a new radiation distribution for the 48 PV cells.

Article's irradiance distribution has been multiplied by a factor so the medium irradiance is 800 suns and 1000 $\frac{W}{m^2}$ per sun. In table 3 and figure 11 this new distribution is presented:

Table 3. Non-uniform irradiance distribution (suns).

	1	2	3	4	5	6
1	432,09	513,50	526,03	519,77	457,14	250,49
2	782,78	926,81	939,33	908,02	820,35	500,98
3	958,12	1089,63	1083,37	1083,37	1095,89	695,11
4	832,88	1114,68	1089,63	1070,84	1077,10	789,04
5	983,17	1095,89	1083,37	1089,63	1089,63	832,88
6	914,29	1070,84	1070,84	1083,37	1077,10	770,25
7	688,85	870,45	908,02	914,29	864,19	619,96
8	225,44	338,16	363,21	344,42	300,59	244,23

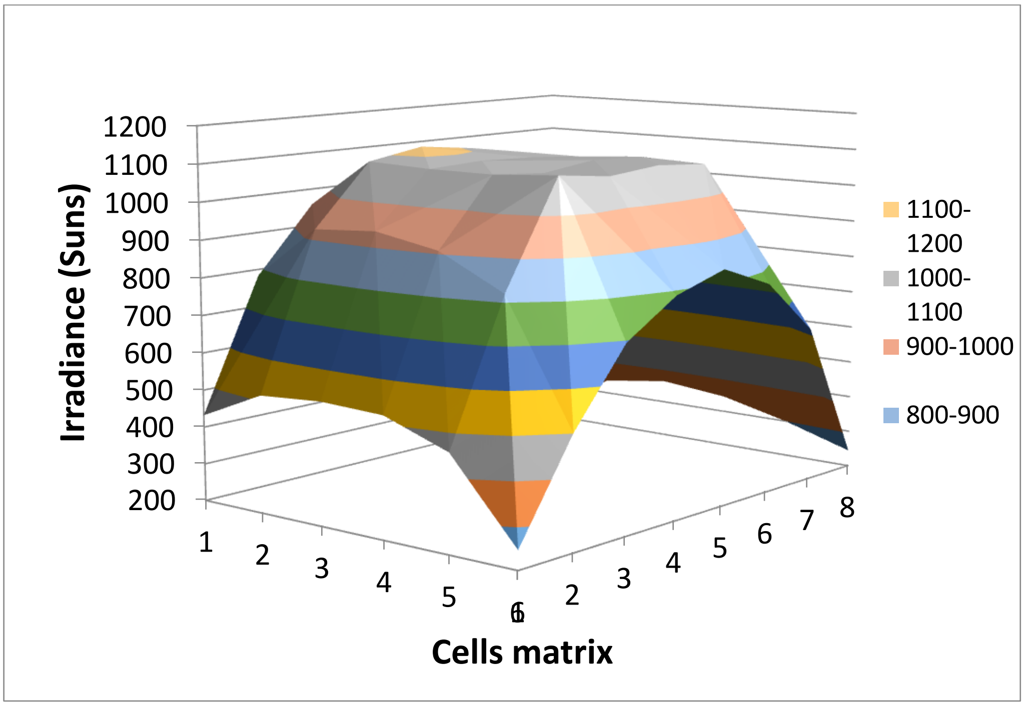

Figure 11. Non-uniform irradiance distribution 3-D model.

As can be seen there are some cells that have a quarter the irradiance of the most irradiated cells. Due to the high radiation, a cooling system is needed. It will be placed under to PV plate.

8.7. Cooling systems

Two cooling systems are studied, microchannels and microfluidic cells, to determine the temperature distribution and how it affects the net power generation.

8.7.1. Microchannels cooling system

The classical method used as a heat sink is microchannels [10] which consists of numerous channels with an hydraulic diameter below 1 mm. The coolant passes through them and it has been demonstrated that increases the heat flux compared to planar heat sinks. A microchannels heat sink 3-D model can be seen is figure 5:

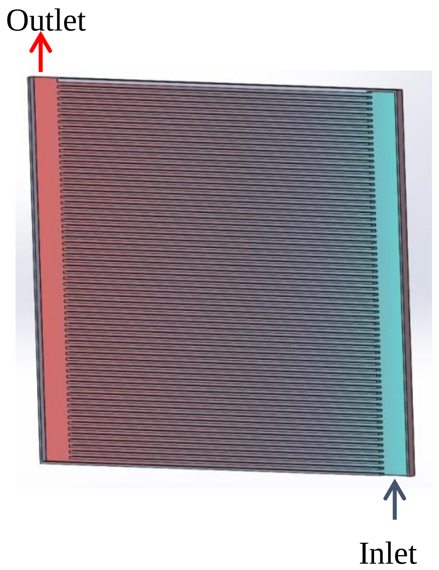

Figure 12. Model formed by parallel microchannel.

The microchannels plate would be located under the CPV dense array.

In figure 13 a representation of the 48 CPV array the coolant flow direction is shown:

1	2	3	4	5	6
7	8	9	10	11	12
13	14	15	16	17	18
19	20	21	22	23	24
25	26	27	28	29	30
31	32	33	34	35	36
37	38	39	40	41	42
43	44	45	46	47	48

Figure 13. CPV cells distribution and coolant flow direction.

Every cell is 1 cm wide and long so there is a total of 6 cm to cover with microchannels. A single microchannel measures 0.6 mm so 100 microchannels are needed to cover all the area. The total water flow needed is: $Q = 8.25x10^{-8}\frac{m^3}{s}$, the pressure drop is: $PD = 29069\ Pa$. The pumping power is equal to:

$$P = \rho \cdot g \cdot Q \cdot PD = \mathbf{2.396 \cdot 10^{-4}\ W}$$

The calculated temperature distribution for microchannels cooling system and the non-uniform irradiance distribution is presented in table 4 and figure 14:

Table 4. Calculated temperature distribution for microchannels and non-uniform irradiance distribution (K).

	1	2	3	4	5	6
1	325,61	327,96	328,53	327,81	324,88	318,72
2	339,91	343,76	344,45	343,10	339,12	329,90
3	352,45	356,71	357,23	356,39	353,73	342,19
4	358,87	366,21	366,67	365,46	362,60	352,43
5	369,70	374,43	375,09	374,28	371,09	361,07
6	375,03	380,71	381,85	381,15	377,47	366,19
7	374,05	380,46	382,52	381,64	376,98	366,76
8	365,75	371,03	372,90	371,50	366,99	360,41

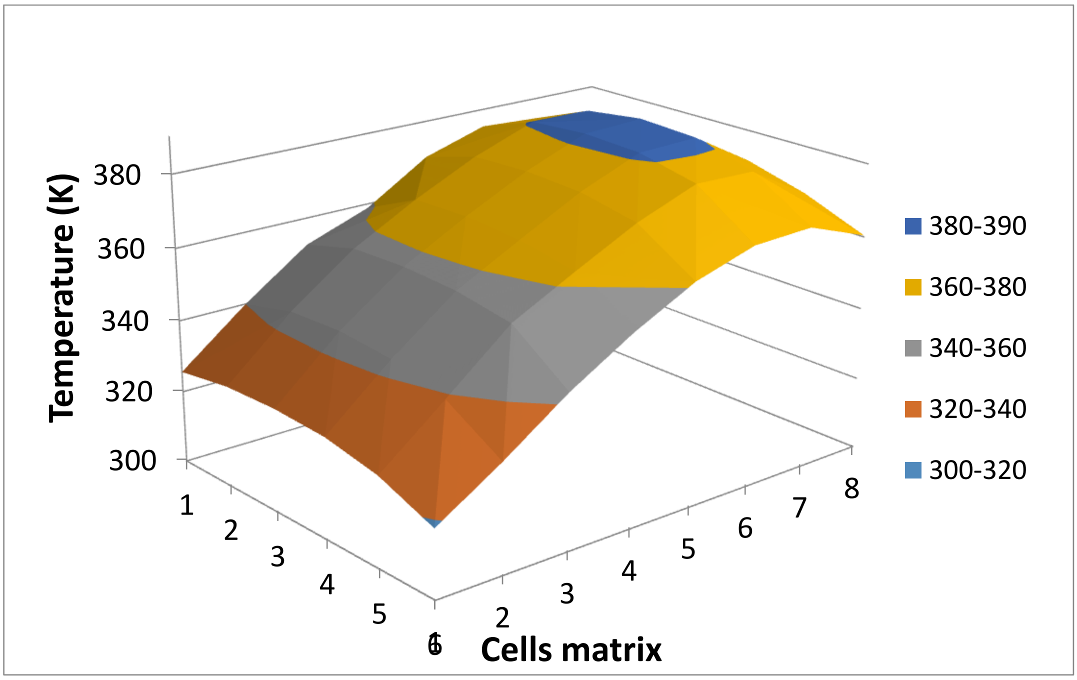

Figure 14. Microchannels temperature distribution for the non-uniform irradiance distribution.

The average temperature is 359.24 K and the maximum temperature difference is **63.81** K.

As it can be seen the microchannels cooling system creates an ascendant temperature distribution because the coolant is increasing its temperature on its way through the channels. This makes a general non-uniform temperature distribution.

When the irradiance is fixed to 800 suns for the 48 cells, the temperature distribution is presented in table 5 and figure 15:

Table 5. Calculated temperature distribution for microchannels and uniform irradiance (K).

	1	2	3	4	5	6
1	336,71	336,73	336,74	336,74	336,73	336,71
2	342,23	342,24	342,25	342,25	342,24	342,23
3	348,79	348,80	348,81	348,81	348,80	348,79
4	355,53	355,55	355,55	355,55	355,55	355,53
5	362,29	362,31	362,31	362,31	362,31	362,29
6	368,96	368,98	368,99	368,99	368,98	368,96
7	375,28	375,31	375,31	375,31	375,31	375,28
8	380,24	380,28	380,29	380,29	380,28	380,24

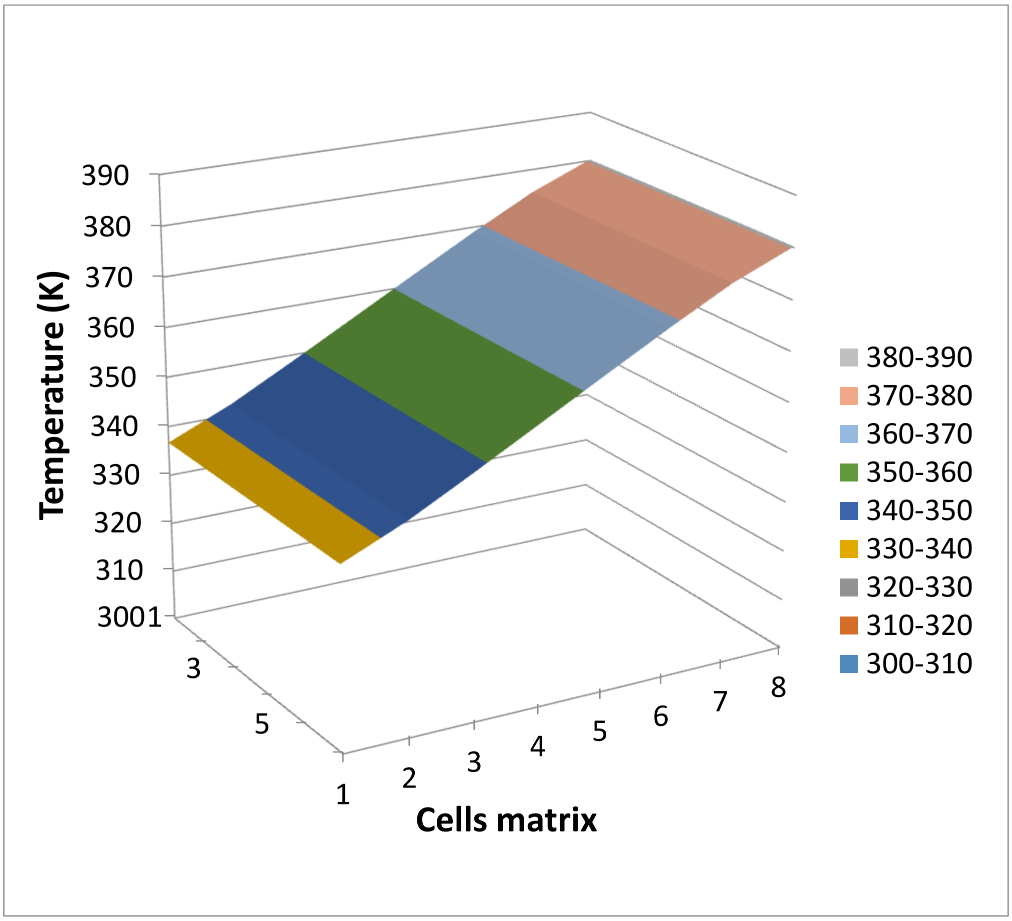

Figure 15. Microchannels temperature distribution for uniform irradiance.

The average temperature is 358.77 K and the maximum temperature difference is 43.58 K.

The calculation method for the microchannels scenario is presented in Annex 2.

8.7.2. Microfluidic cells cooling system

Microfluidic cells are a cooling system studied in the European Project Streams [11]. In this device, the coolant is distributed towards a matrix of microfluidic cells. Each micro-fluidic cell has a temperature controlled microvalve that self-adapts the cell flow rate to the local temperature. The microvalves adapt the coolant flow rate in each cell to the minimum required to maintain a desired temperature, allowing higher flow rates when the temperature rises due to increase local heat load. The microfluidic cells 3-D model is presented in figure 16:

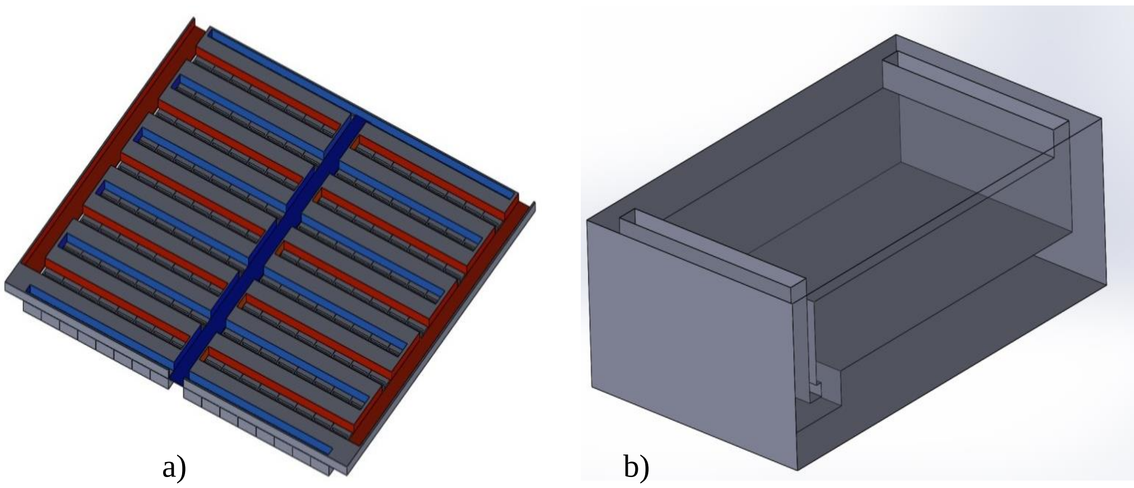

Figure 16. a) Coolant distributor and matrix of cells. b) Single cell.

There are 48 microfluidic cells, one per each PV cell. The water flows for each cell are shown in table 6:

Table 6. Water flow for each microfluidic cell (m^3/s)

	1	2	3	4	5	6
1	1,13E-07	1,28E-07	1,30E-07	1,29E-07	1,17E-07	7,69E-08
2	1,73E-07	1,96E-07	1,98E-07	1,93E-07	1,79E-07	1,25E-07
3	2,00E-07	2,20E-07	2,19E-07	2,19E-07	2,21E-07	1,59E-07
4	1,81E-07	2,24E-07	2,20E-07	2,17E-07	2,18E-07	1,74E-07
5	2,04E-07	2,21E-07	2,19E-07	2,20E-07	2,20E-07	1,81E-07
6	1,94E-07	2,17E-07	2,17E-07	2,19E-07	2,18E-07	1,71E-07
7	1,58E-07	1,87E-07	1,93E-07	1,94E-07	1,86E-07	1,46E-07
8	7,16E-08	9,47E-08	9,96E-08	9,60E-08	8,72E-08	7,56E-08

The total water flow is: $Q = 8.32 \cdot 10^{-6} \frac{m^3}{s}$ and the pumping power is:

$$P = \mathbf{4.16 \cdot 10^{-5}}\ \boldsymbol{W}$$

The calculations and more information are found in Gonzalo Sisó Soler's project.

The calculated temperature distribution for microfluidic cells cooling system and the non-uniform irradiance distribution is presented in table 7 and figure 17:

Table 7. Calculated temperature distribution for microfluidic cells and non-uniform irradiance (K).

	1	2	3	4	5	6
1	351,39	353,71	354,05	353,88	352,14	344,74
2	359,86	362,52	362,74	362,19	360,59	353,37
3	363,06	365,17	365,07	365,07	365,27	358,06
4	360,83	365,55	365,17	364,88	364,98	359,99
5	363,47	365,27	365,07	365,17	365,17	360,83
6	362,30	364,88	364,88	365,07	364,98	359,62
7	357,93	361,52	362,19	362,30	361,41	356,38
8	343,58	348,27	349,16	348,50	346,85	344,46

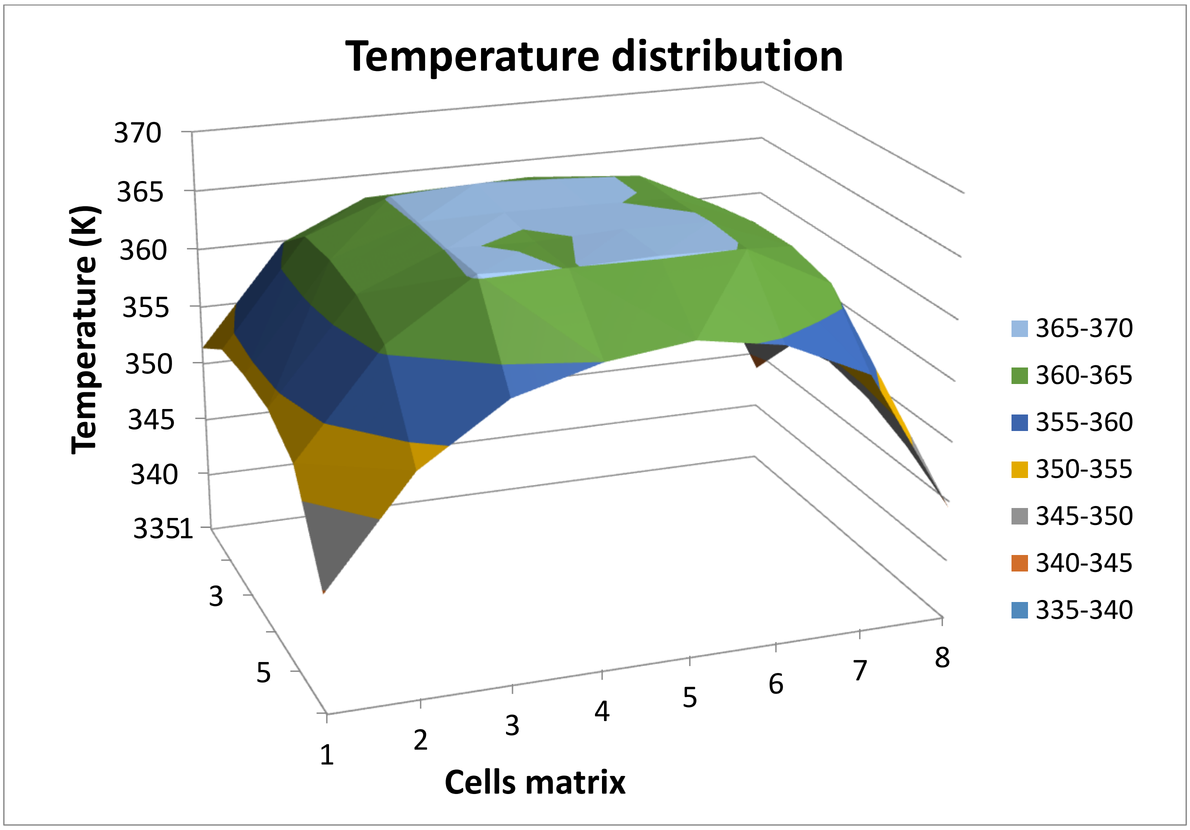

Figure 17. Microfluidic cells temperature distribution for the non-uniform irradiance distribution.

The average temperature is 359.24 K and the maximum temperature difference is **22** K.

So both microchannels and microfluidic cells have the same average temperature. Microfluidic cells has a more uniform temperature distribution than microchannels.

When the irradiance is fixed to 800 suns for the 48 cells, the temperature distribution is presented in table 8:

Table 8. Calculated temperature distribution for microfluidic cells and uniform irradiance (K).

	1	2	3	4	5	6
1	358,77	358,77	358,77	358,77	358,77	358,77
2	358,77	358,77	358,77	358,77	358,77	358,77
3	358,77	358,77	358,77	358,77	358,77	358,77
4	358,77	358,77	358,77	358,77	358,77	358,77
5	358,77	358,77	358,77	358,77	358,77	358,77
6	358,77	358,77	358,77	358,77	358,77	358,77
7	358,77	358,77	358,77	358,77	358,77	358,77
8	358,77	358,77	358,77	358,77	358,77	358,77

The average temperature is 358.77 K.

The calculations and more information are found in Gonzalo Sisó Soler's project.

The main goal is keeping the same medium temperature for both microchannels and microfluidic cells scenarios. Then, the differences between having a more uniform temperature distribution can be measured.

8.8. Electrical configurations

Once the two different irradiance and temperature distributions have been defined, different electrical configurations of the 48 PV cells have to be studied. This study will contribute to the understanding of how the no uniform irradiance and temperature affects the system. The different electrical configurations are:

8.8.1. Series configuration, 48x1

In this configuration the 48 PV cells are connected completely in series. All cells are considered to have a bypass diode with a voltage of 0.5V. The maximum electrical power for this configuration has been found using the "Solver" tool by fixing the same current for all the cells. In figure 18 an example can be seen:

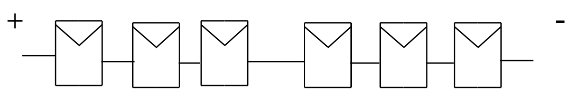

Figure 18. 48x1 configuration.

8.8.2. Parallel configuration, 1x48

In this configuration the 48 PV cells are connected in parallel. The maximum electrical power has been found using the "Solver" tool by fixing the same voltage for all the cells. In figure 19 an example can be seen:

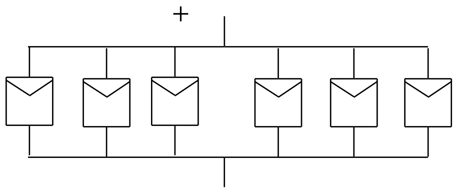

Figure 19. 1x48 configuration.

8.8.3. Matrix configuration, 6x8

In this configuration there are 8 series of 6 cells each one connected in parallel. The 8 series have the same voltage. In this configuration it has been necessary to use Visual Basics for Applications and the "Solver" tool, by giving consignment voltages for the 8 series and finding the current for each series that makes the series voltage equal to the consignment voltage. Then, when having the hole I-V curve finding the maximum electrical power point. In figure 20 an example can be seen:

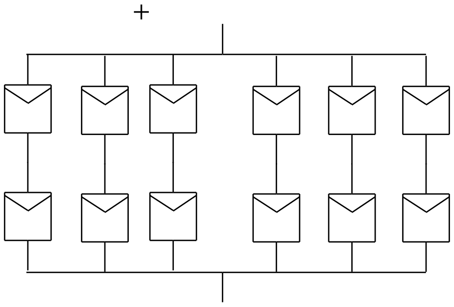

Figure 20. 6x8 configuration.

8.8.4. Modules configuration, 6x8x1

In this configuration there are 8 modules of 6 cells connected in parallel each one, the 8 modules have the same current. In this configuration it has been necessary to use Visual Basics for Applications and the "Solver" tool, by giving consignment currents for the 8 modules and finding the voltage for each module that makes the total module current equal to the consignment current. In figure 21 an example can be seen:

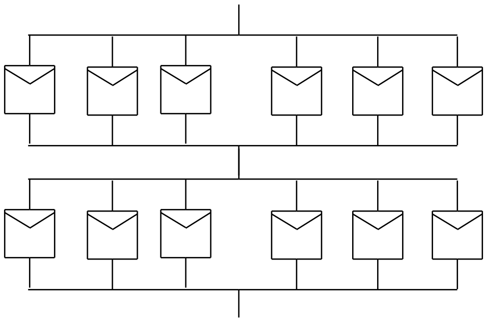

Figure 21. 6x8x1 configuration.

9. Results and discussion

The pumping power is not considered in any result due to the low values obtained for this system.

Both microchannels and microfluidic cells cooling systems are studied for the non-uniform and uniform irradiance distribution for different electrical configurations.

9.1. Cells individually connected

This scenario is an ideal one, where every single cell of the dense array can produce energy without being influenced by the other cells. This scenario is impossible to build but has been calculated just to know the maximum theoretical output power for the 48 PV cells. The results are presented in table 9:

Table 9. Power comparison for the non-connected cells (W).

	Microchannels	Microfluidic cells	Increment
Non-uniform irradiance	1331.89	1333.18	0.1%
Uniform irradiance	1339.21	1339.15	-0.005%
Increment	0.55%	0.45%	

It can be seen that when cells are not interconnected the differences in energy production are not important because there are not mismatch errors.

More information can be found in Annex 3.

9.2. Series configuration, 48x1

The results are presented in table 10:

Table 10. Power comparison for the 48x1 configuration (W).

	Microchannels	Microfluidic cells	Increment
Non-uniform irradiance	857.8	860.97	0.37%
Uniform irradiance	1338.97	1339.15	0.01%
Increment	56.09%	55.54%	

The differences obtained between the two cooling systems are small. This is because the temperature differences between the cells affect the voltage output. In 48x1, all the cells share the same current but can have different voltages. The hottest cell voltage is reduced but the coolest one is augmented so it is almost equilibrated in these conditions of temperature and irradiance.

The difference between the two irradiance distributions is very important. This happens because the irradiance affects the current of the cell and as all the cells must have the same current, the maximum power point implies a current that makes some cells consume energy. Then the current passes through the bypass diode which is considered to have a voltage drop of 0.5V.

In figure 22 the I-V and P-V curve can be seen:

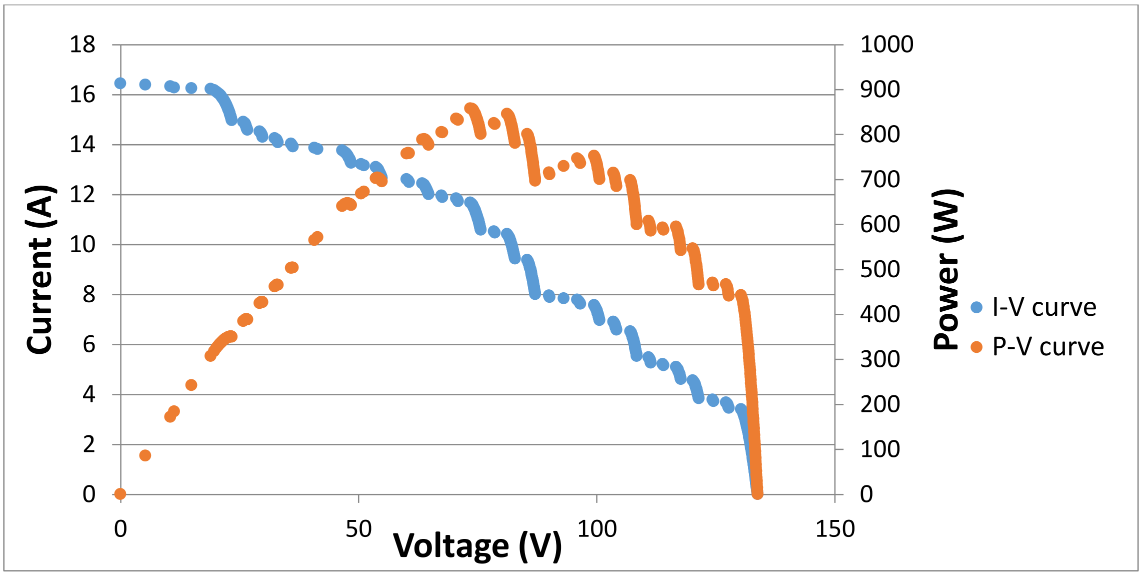

Figure 22. 48x1 I-V and P-V curve for microchannels and non-uniform irradiance.

The irregularities exist due to the current passing through the bypass diode in some cells.

In order to understand better what is happening in this scenario, another study has been done by changing the temperature distribution and notably reducing the temperature of the most irradiated cells while maintaining the same average temperature as it can be seen in table 11:

Table 11. Temperature distribution that lowers the temperature of the most irradiated cells (K).

	1	2	3	4	5	6
1	365,61	367,96	368,53	367,81	364,88	358,72
2	379,91	343,76	344,45	343,10	339,12	369,90
3	392,45	298,66	299,11	298,39	296,17	382,19
4	398,87	306,62	307,00	305,99	303,60	392,43
5	409,70	313,50	314,05	313,37	310,71	401,07
6	415,03	318,76	319,72	319,13	316,05	406,19
7	414,05	380,46	382,52	381,64	376,98	406,76
8	405,75	411,03	412,90	411,50	406,99	400,41

The power generated is:

$$Power = 904.21\ W$$

Which is **5.41%** more electrical power than the microchannels scenario.

So the configuration produces more power if the cells that have more irradiance are cooler than the others but at the same time the current can't raise too much because there are other cells that are consuming power.
Other information related to the 48x1 configuration can be found in Annex 4.

9.3. Matrix configuration, 6x8

The results are presented in table 12:

Table 12. Power comparison for the 6x8 configuration (W).

	Microchannels	Microfluidic cells	Increment
Non-uniform irradiance	1036.3	1075.8	3.81%
Uniform irradiance	1317.42	1339.15	1.65 %
Increment	27.13%	24.48%	

The differences obtained between the two cooling systems are relevant. This is because the temperature differences between the cells affect the power output and as the 8 series share the same voltage, for the same voltage the hottest cells will produce less energy.

The difference between the two irradiance distributions is again very important. There are again cells connected in series which are affected by the non-uniform irradiance.
In figure 23 the I-V and P-V curve can be seen:

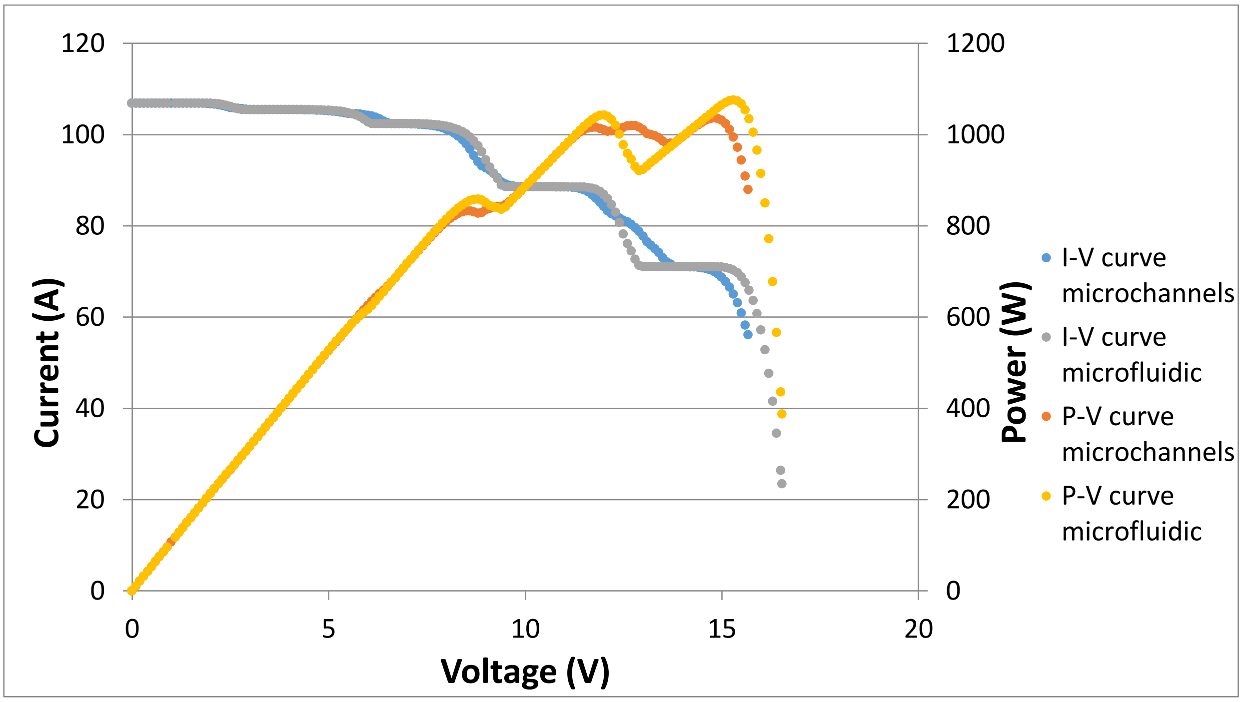

Figure 23. 6x8 I-V and P-V curves for microchannels and microfluidic cells and non-uniform irradiance.

The irregularities exist due to the current passing through the bypass diode in some cells. The microfluidic cells cooling system allows more voltage and power as it can be seen.

Other information related to the 6x8 configuration can be found in Annex 5.

9.4. Modules configuration, 6x8x1

This electrical configuration has the characteristic of sharing the same current for all 8 groups of 6 cells in parallel and each group has a voltage for all the cells.

The results are presented in table 13:

Table 13. Power comparison for the 6x8x1 configuration (W).

	Microchannels	Microfluidic cells	Increment
Non-uniform irradiance	580.21	581.69	0.26%
Uniform irradiance	1338.97	1339.15	0.013 %
Increment	130.77%	130.22%	

For the non-uniform irradiance and microchannels for example, this electrical configuration has 2 limitations:

1. Maximum current of the system. Fixing the voltage of all the groups to 0 determine the maximum current allowed that will be the lowest one. The worst group of cells in terms of received irradiance is the limiting one. This can be seen in table 14:

Table 14. Maximum limiting current of every group of cells.

	Current on each cell (A)							
	1	2	3	4	5	6	Vmin (V)	Imax (A)
1	6,56	7,79	7,98	7,89	6,94	3,80	0,00	40,95
2	11,88	14,06	14,25	13,78	12,45	7,60	0,00	74,02
3	14,54	16,53	16,44	16,44	16,63	10,55	0,00	91,12
4	12,64	16,91	16,53	16,25	16,34	11,97	0,00	90,64
5	14,92	16,63	16,44	16,53	16,53	12,64	0,00	93,69
6	13,87	16,25	16,25	16,44	16,34	11,69	0,00	90,83
7	10,45	13,21	13,78	13,87	13,11	9,41	0,00	73,83
8	3,42	5,13	5,51	5,23	4,56	3,71	0,00	27,55

$$I_{Max} = 27.55\ A$$

2. Minimum current of the system. Blocking diodes are not considered so there is a maximum voltage on each group of cells that makes a first cell produce 0 amperes. Then the group that fulfils this characteristic with the highest current determines the minimum current of the system. This can be seen in table 15:

Table 15. Minimum limiting current of every group of cells.

	Current on each cell (A)							
	1	2	3	4	5	6	Vmax (V)	Imin (A)
1	0,90	1,35	1,33	1,49	1,51	0,00	2,92	6,59
2	0,61	0,31	0,00	0,48	1,64	1,03	2,91	4,07
3	1,58	0,52	0,00	0,67	2,81	2,94	2,85	8,52
4	1,36	0,74	0,00	0,65	2,77	3,85	2,79	9,37
5	2,22	0,70	0,00	0,71	2,95	4,36	2,74	10,93
6	2,11	0,85	0,00	0,72	3,13	4,07	2,69	10,87
7	1,27	0,70	0,00	0,65	2,53	3,02	2,67	8,17
8	0,00	0,63	0,56	0,62	0,91	1,13	2,59	3,85

$$I_{Min} = 10.93\ A$$

In figure 24 the I-V and P-V curve can be seen:

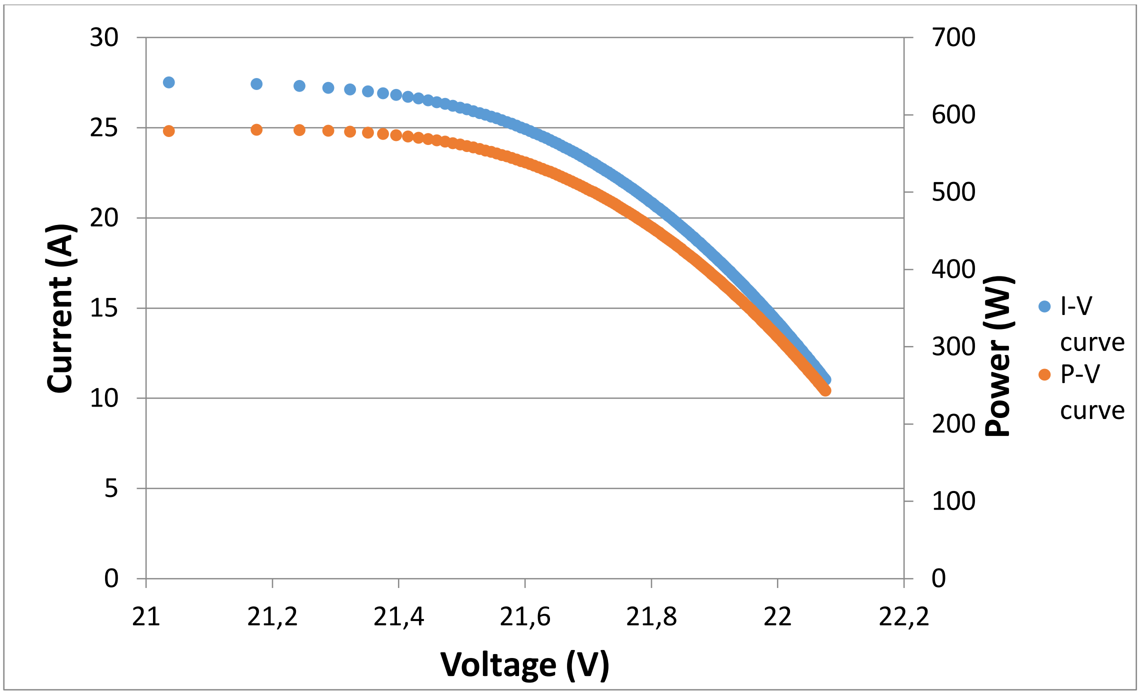

Figure 24. 6x8x1 I-V and P-V curves for microchannels and non-uniform irradiance.

This situation limits the electrical output power of the system as it can be seen in the figure and compared to other electrical configurations. The differences between the 2 different cooling systems cannot be seen due to this problem.

9.4.1 Solution proposed for the modules configuration

In order to solve this inconvenient, power supplies could be attached to the system. One power supply per group of 6 cells and connected in parallel as shown in figure 25:

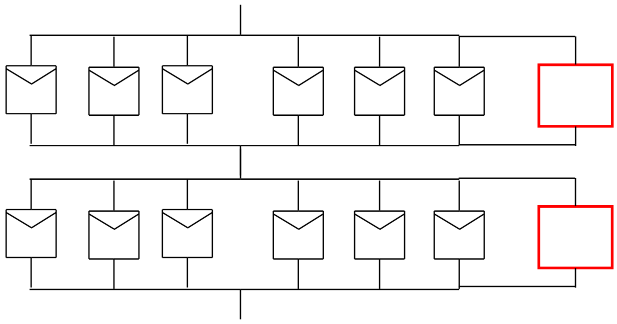

Figure 25. Power supplies attached to the 6x8x1 configuration.

The main idea is that the power supply of the best group doesn't produce energy while the rest are introducing as much current in the system as needed to be in equilibrium with best group of cells. This is shown in table 16:

Table 16. Analysis of the introduction of power supplies for the 6x8x1 configuration with microchannels and non-uniform irradiance.

$I_{per\ group}\ (A)$	$V_{per\ group}\ (V)$	$P_{photovoltaic}\ (W)$	$I_{power\ supply}$	$P_{power\ supply}\ (W)$	P_{total} (W)
39,19	2,58	101,02	49,54	127,69	228,71
70,65	2,54	179,73	18,08	45,99	225,71
86,72	2,48	215,10	2,01	4,98	220,09
86,06	2,42	208,29	2,67	6,47	214,75
88,73	2,37	209,89	0,00	0,00	209,89
85,86	2,32	199,20	2,87	6,65	205,85
69,74	2,29	159,94	18,99	43,55	203,50
26,03	2,23	58,11	62,70	140,00	198,12
Total		1331,28		375,34	1706,62

As the efficiency of a normal power supply is around 90%, the power losses are:

$$P_{losses} = \frac{375.34}{0.9} - 375.34 = 41.7\ W$$

So the electrical output of this configuration with the use of power supplies is presented in table 17:

Table 17. 6x8x1 electrical power with the use of power supplies.

	Microchannels	Microfluidic cells	Increment
Non-uniform irradiance	1289.58	1291.46	0.15%

The increment in power the microfluidic cells cooling system is low but the increment respect not using the power supplies is **122.26%**.

The regulation of the power supplies is not studied in this project.

9.5. Parallel configuration, 1x48

The results are presented in table 18:

Table 18. Power comparison for the 1x48 configuration (W).

	Microchannels	Microfluidic cells	Increment
Non-uniform irradiance	1309.9	1333.04	1.78%
Uniform irradiance	1317.43	1339.15	1.65 %
Increment	0.57%	0.46%	

The differences obtained between the two cooling systems are relevant. This is because the temperature differences between the cells affect the power output and as the 48 cells share the voltage in this configuration, the hottest cells produce less energy.

The difference between the two irradiance distributions is not very important. This is because if one cell has half the irradiance of another, the bad one won’t consume energy because there are no bypass diodes. The only problem can occur if the cell with the lowest irradiance needs to accomplish a superior voltage than its open circuit voltage. But in this analysis with the worst conditions of:

- Irradiance: 225.44 suns.
- Temperature: 365.74 K

And the best condition cell of:

- Irradiance: 1089.63 suns.
- Temperature: 366.67 K.

This risky situation has not happened so we can affirm that for non-uniform irradiances distributions, the 1x48 array is the best one tested.

In figure 26 the I-V and P-V curve can be seen:

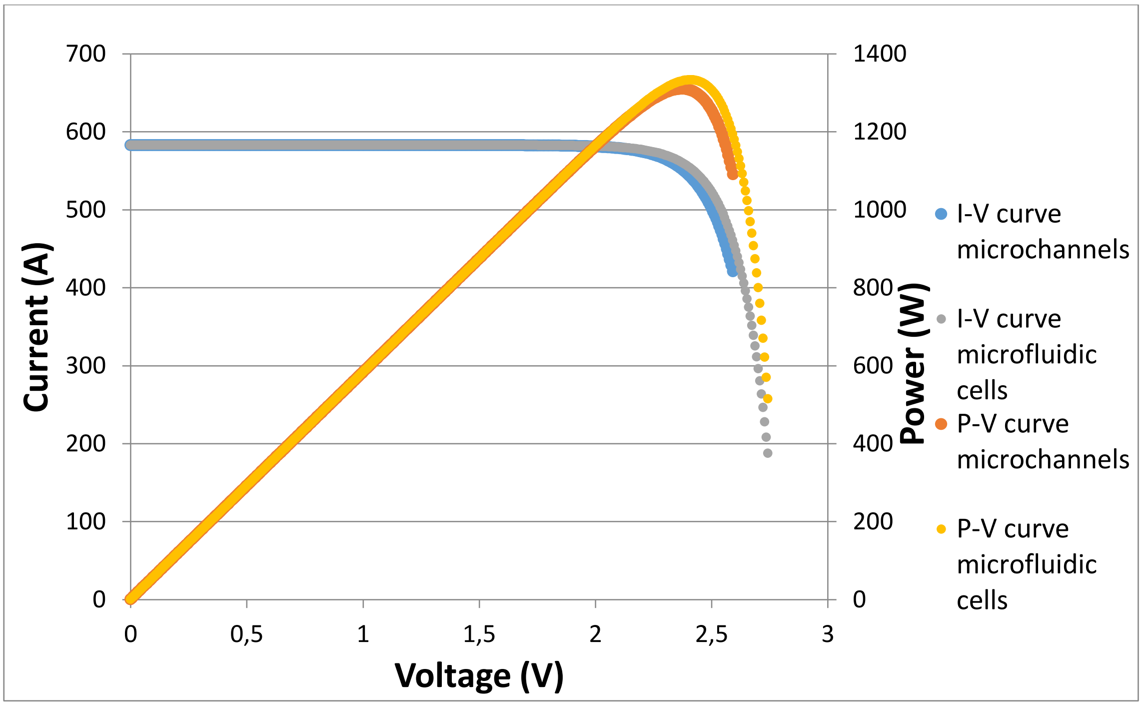

Figure 26. 1x48 I-V and P-V curves for microchannels and microfluidic cells and non-uniform irradiance.

As it can be seen in the figure, the big disadvantage of this configuration is that is obtained around 550 amperes which will generate high amounts of heat losses.

In order to understand better what is happening in this scenario, another study has been done by changing the temperature distribution and notably increasing the temperature of the most irradiated cells while maintaining the same average temperature as it can be seen in table 19:

Table 19. Temperature distribution that increases the temperature of the most irradiated cells (K).

	1	2	3	4	5	6
1	285,61	287,96	288,53	287,81	284,88	278,72
2	299,91	343,76	344,45	343,10	339,12	289,90
3	312,45	414,74	415,35	414,37	411,28	302,19
4	318,87	425,79	426,32	424,92	421,59	312,43
5	329,70	435,34	436,11	435,17	431,46	321,07
6	335,03	442,65	443,98	443,15	438,88	326,19
7	334,05	380,46	382,52	381,64	376,98	326,76
8	325,75	331,03	332,90	331,50	326,99	320,41

The power generated is:

$$Power = 1133.33\ W$$

Which is **13.48%** less electrical power than the microchannels scenario.

So in the parallel configuration, the electrical power is notably reduced by having the most irradiated cells at a higher temperature.

The parallel configuration is more affected by a less uniform temperature distribution than the series one as it can be seen in (9.2. Series configuration, 48x1).

Other information related to the 1x48 configuration can be found in Annex 6.

9.6. Results summary

In table 20 all the results have been reunited:

Table 20. Maximum power generated in every scenario studied (W).

	Microchannels	
	Non-uniform irradiance	Uniform irradiance
48x1	857.8	1338.97
6x8	1036.3	1317.42
6x8x1	580.21	1338.97
6x8x1 power supplies	1289.58	-
1x48	1309.9	1317.42
	Microfluidic cells	
	Non-uniform irradiance	Uniform irradiance
48x1	860.97	1339.15
6x8	1075.80	1339.15
6x8x1	581.69	1339.15
6x8x1 power supplies	1291.46	-
1x48	1333.04	1339.15

10. Conclusions

From all the calculations and results, the following conclusions are presented:

- Microfluidic cells cooling system has uniformed the temperature distribution which has incremented the electrical power generation in all the scenarios studied.

- In a CPV dense array, the cooler the most irradiated cells are, the more power is produced. This statement is more important in parallel than in series configuration.

- Matrix configuration has been the one that has incremented more the electrical power when using microfluidic cells as a cooling system, up to 3.81%.

- Parallel configuration is the less affected by the non-uniform irradiance distribution so is the configuration with the highest electrical power under non-uniform conditions.

- Modules configuration with power supplies has the second highest electrical power generation in non-uniform irradiance conditions.

- Modules configuration has 2 limiting problems when having a non-uniform irradiance, maximum and minimum current of the system. Under the current irradiance conditions, these limitations make this configuration the worst one.

- When adding power supplies to the modules configuration allows the configuration to obtain 122.26% more power.

- Series configuration produces the least electrical power because a high current makes the less irradiated cells consume power through the bypass diode.

- Obtaining a uniform irradiance distribution is way more effective in terms of increased power for series connected PV cells than obtaining a uniform temperature distribution.

- Series configuration has the lowest current while parallel configuration has the highest one, from 11.6A to 551A. So the more cells in parallel, the higher the current obtained and the heat losses from the Joule effect.

11. References

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12. Annex 1

Temperature calibration of the I-V curve

The results of this solution can be seen in tables 21, 22 and 23:

Short circuit current J_{SC} (A)

Table 21. Short circuit current calibration for different temperatures.

	Datasheet	Calculated	Error
25ºC	7.5863900	7.586390	1.02141E-13
40ºC	7.5865130	7.586513	9.37916E-13
50ºC	7.5865950	7.586595	3.68505E-12
75ºC	7.5868000	7.586800	8.05711E-11
100ºC	7,5870050	7,587005	2,75118E-08

Open circuit voltage V_{OC} (V)

Table 22. Open circuit voltage calibration for different temperatures.

	Datasheet	Calculated	Error
25ºC	3.130	3.131	0.000618
40ºC	3.034	3.035	0.001308
50ºC	2.970	2.971	0.001341
75ºC	2.810	2.810	0.000000
100ºC	2,650	2,647	0,00268

Maximum power voltage V_{mp} (V)

Table 23. Maximum power voltage calibration for different temperatures.

	Datasheet	Calculated	Error
25ºC	2.7809	2.7809	1.75446E-05
40ºC	2.6804	2.6773	0.00307
50ºC	2.6134	2.6082	0.005131
75ºC	2.4459	2.4357	0.010172
100ºC	2,2784	2,2635	0,014866

Figure 27 shows the P-V curve for different temperatures:

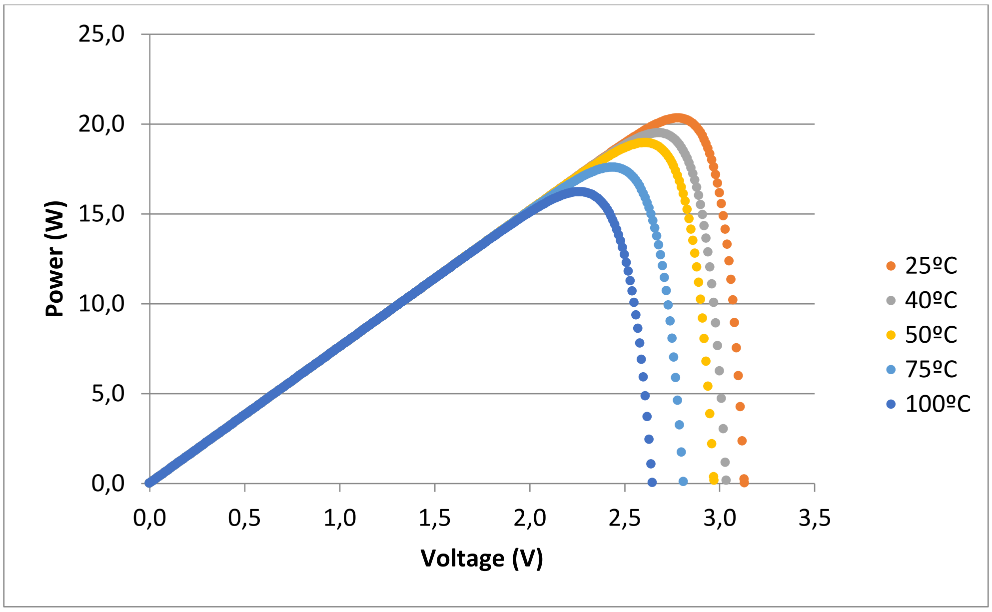


Figure 27. P-V curve for different temperatures using the calibrated model at 500 suns.

Figure 28 shows the I-V curve for different irradiances:

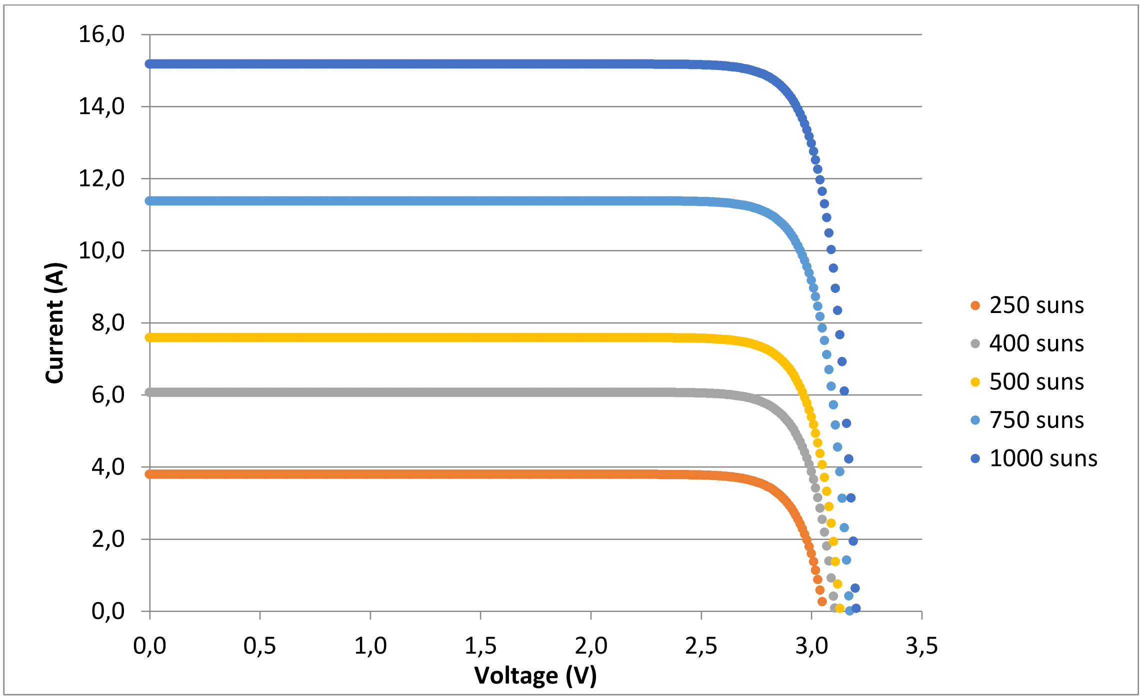


Figure 28. I-V curve for different irradiances using the calibrated model at 25ºC.

Figure 29 shows the P-V curve for different irradiances:

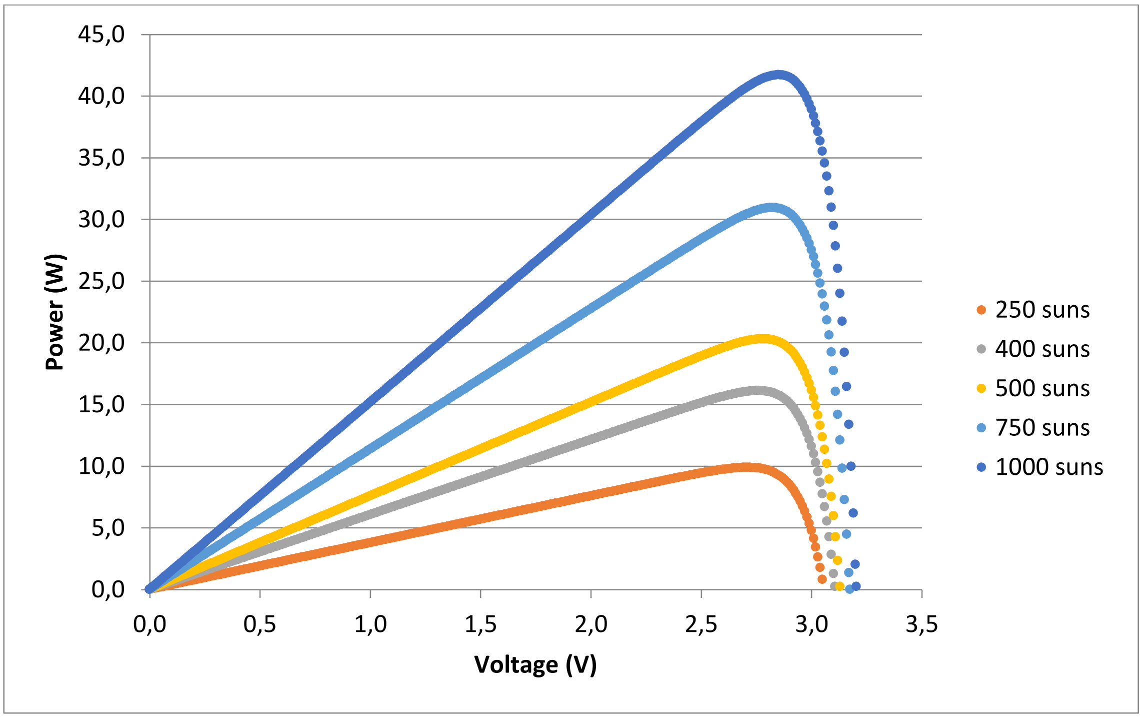


Figure 29. P-V curve for different irradiances using the calibrated model at 25 ºC.

13. Annex 2

Microchannels temperature distribution

In order to calculate the temperature distribution of this cooling system, an approximation is done by considering it as a 3 layer system and calculated as a thermal resistance model. The 3 layers that compound the model are:

- Cell layer. Where the PV cells are located. It contains 48 nodes corresponding to the 48 cells that are studied. The nodes are located in the middle of the PV cells.
- Bulk layer. It is made of silicon and contains 48 nodes.
- Fluid layer. Represents the coolant. It contains 48 nodes. The nodes are located in the middle of the fluid layer.

In figure 30 a scheme of the system can be seen:

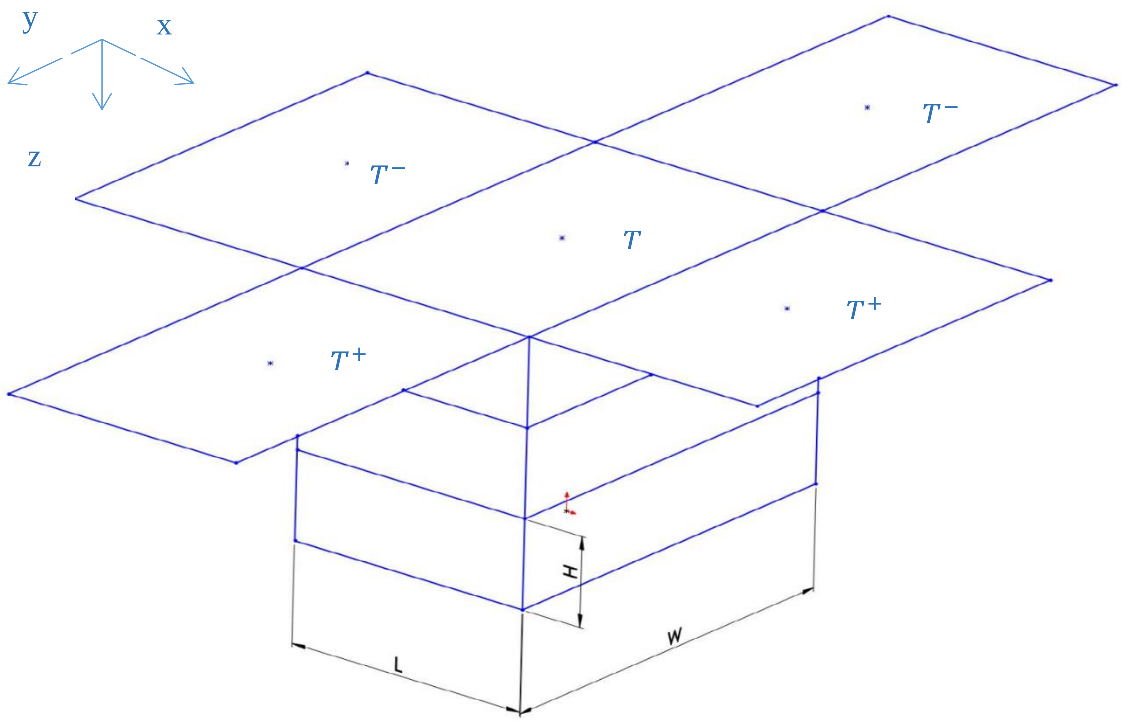


Figure 30. Schematic model of the resistance system that has been used to calculate the microchannels temperature distribution.

Assumptions

1. Steady state.
2. Conduction between PV cells is not considered.
3. 3-D geometry.
4. Convection from the fluid layer to ambient is not considered.
5. Heat transfer in the fluid only occurs in the flow direction.
6. Constant material properties.

To calculate the temperature distribution for the microchannels cooling system, the second Fourier Law is solved for finite increments.

$$C\dot{T} = k\nabla T \tag{1}$$

The equation for the 48 cell layer nodes is:

$$0 = v_a \cdot Q - v_a \cdot cc_a \cdot (T_c - T_a) - cc_z \cdot (T_c - T_b) \tag{2}$$

The equation for the 48 bulk layer nodes is:

$$0 = -cc_x \cdot (T_b - T_b^+) - cc_x \cdot (T_b - T_b^-) - cc_y \cdot (T_b - T_b^+) - cc_y(T_b - T_b^-) - cc_z \cdot (T_b - T_c) - cc_h \cdot v_f \cdot (T_b - T_f) \tag{3}$$

The equation for the 48 fluid layer nodes is:

$$0 = -cc_h \cdot v_f \cdot \left(T_f - T_b\right) - cc_f \cdot (T_f - T_f^-) \tag{4}$$

The thermal resistance for every node located in the bulk layer is equal to:

$$R = \frac{L/2}{k} \tag{5}$$

The total resistance between 2 nodes is the sum of the thermal resistance of the two nodes:

$$R_T = R_1 + R_2 = \frac{k_2 \cdot L_1 + k_1 \cdot L_2}{2 \cdot k_1 \cdot k_2} \tag{6}$$

The thermal transmittances $cc_x, cc_y \; and \; cc_z$ between 2 nodes are the inverse of the total thermal resistance. It is presented for the 3 space directions as:

$$cc_x = \frac{1}{R_T} = \frac{2 \cdot k_1 \cdot k_2}{L_1 \cdot L_2 \cdot \left(\frac{k_1}{L_1} + \frac{k_2}{L_2}\right)} \tag{7}$$

$$cc_y = \frac{2 \cdot k_1 \cdot k_2}{W_1 \cdot W_2 \cdot \left(\frac{k_1}{W_1} + \frac{k_2}{W_2}\right)} \tag{8}$$

$$cc_z = \frac{2 \cdot k_1 \cdot k_2}{H_1 \cdot H_2 \cdot \left(\frac{k_1}{H_1} + \frac{k_2}{H_2}\right)} \tag{9}$$

The nodes in the first layer are considered to be in the middle of the PV cell so it is necessary to find a corrector factor because the solar irradiance is heating the surface. The energetic balance in the first layer is:

$$J = -k_c \cdot \frac{T - \bar{T}}{\frac{H_c}{2}} = Q - h_a \cdot (\bar{T} - T_a) \tag{10}$$

Isolating the surface temperature $\bar{T}$, the following equation is found:

$$\bar{T} = \frac{Q \cdot H_c + 2 \cdot k_c \cdot T + h_a \cdot H_c \cdot T_a}{2 \cdot k_c + h_a \cdot H_c} \tag{11}$$

Replacing in the energetic balance the surface temperature $\bar{T}$ and simplifying the expression found is:

$$J = -\frac{2 \cdot k_c}{2 \cdot k_c + h_a \cdot H_c} \cdot (h_a \cdot (T - T_a) - Q) \tag{12}$$

The dimensionless corrector factor for the cell layer is:

$$v_a = \frac{2 \cdot k_c}{2 \cdot k_c + h_a \cdot H_c} \tag{13}$$

Analogously, the nodes in the fluid layer are considered to be in the middle of the fluid so the same analysis has to be done between the bulk layer and the fluid layer. The dimensionless corrector factor for the fluid layer is:

$$v_f = \frac{2 \cdot k_b}{2 \cdot k_b + h_f \cdot H_b} \tag{14}$$

In the fluid layer, the heat transfer only occurs in the flow direction and with the bulk by convection. According to "COMPARISION OF THE ENERGY YIELD PREDICTIONS OF STATIONARY AND DYNAMIC SOLAR COLLECTORS MODELS AND THE MODELS' ACCURACY IN THE DESCRIPTION OF A VACUUM TUBE COLLECTOR" written by Jürgen Schnieders, heat transfer in the perpendicular direction of the flow's one is neglected.

Also the thermal transmittance due to the coolant drag is:

$$cc_f = \frac{\rho_f \cdot c_f \cdot H_f \cdot v_{ff} \cdot \zeta}{L} \quad (15)$$

<u>Properties and characteristics</u>

Cell layer

The used material is germanium. The germanium properties are:

- Thermal conductivity, $k_c = 59.9 \frac{W}{K \cdot m}$
- Density, $\rho_c = 5323 \frac{kg}{m^3}$
- Specific heat, $c_c = 320 \frac{J}{K \cdot kg}$
- Air convective coefficient, $cc_a = 20 \frac{W}{m^2 \cdot K}$

Dimensions

- $H_c = 0.001\, m$
- $L_c = W_c = 0.01\, m$

Bulk layer

The used material is silicon. The silicon properties are:

- Thermal conductivity, $k_b = 148 \frac{W}{K \cdot m}$
- Density, $\rho_b = 2330 \frac{kg}{m^3}$
- Specific heat, $c_b = 700 \frac{J}{K \cdot kg}$

Dimensions

- $H_b = 0.00015\ m$
- $L_b = W_b = 0.01\ m$

Fluid layer

The fluid is water. The water properties are:

- Density, $\rho_f = 1000\,\frac{kg}{m^3}$
- Specific heat, $c_f = 4184\,\frac{J}{K\cdot kg}$
- Convective coefficient with the bulk, $cc_h = 47500\,\frac{W}{m^2\cdot K}$
- Water speed, $v_{ff} = 1.4\,\frac{m}{s}$

Dimensions

- $H_f = 0.0002\ m$
- $L_f = W_f = 0.01\ m$

The convective coefficient for microchannels was determined in a COMSOL MULTYPHISICS analysis.

So there is a system of 144 equations and 144 unknowns. It is solved using the Solver program ran by Excel.

Nomenclature

C	specific heat per unit of area $\left(\frac{J}{m^2 \cdot K}\right)$	R	thermal resistance $\left(\frac{K \cdot m^2}{W}\right)$
c_b	specific heat of silicon $\left(\frac{J}{K \cdot kg}\right)$	T_a	air temperature (K)
c_c	specific heat of germanium $\left(\frac{J}{K \cdot kg}\right)$	T_b	bulk node temperature (K)
c_f	specific heat of water $\left(\frac{J}{K \cdot kg}\right)$	T_c	cell node temperature (K)
cc_a	air convective coefficient $\left(\frac{W}{m^2 \cdot K}\right)$	T_f	fluid node temperature (K)
cc_h	water convective coefficient $\left(\frac{W}{m^2 \cdot K}\right)$	$\bar{T}$	superficial temperature (K)
cc_f	thermal transmittance due to the coolant drag $\left(\frac{W}{m^2 \cdot K}\right)$	$\dot{T}$	temperature derivative $\left(\frac{K}{s}\right)$
cc_x, cc_y, cc_z	thermal transmittances for the 3 space directions $\left(\frac{W}{m^2 \cdot K}\right)$	v_a	corrector factor for the cell nodes
J	thermic flux $\left(\frac{W}{m^2}\right)$	v_f	corrector factor for the fluid nodes
H_c, H_b, H_f	height of the 3 layers (m)	v_{ff}	water speed $\left(\frac{m}{s}\right)$
L_c, L_b, L_f	length of the 3 layers (m)	ρ_b, ρ_c, ρ_f	density of the Germanium, Silicon and Water $\left(\frac{kg}{m^3}\right)$
W_c, W_b, W_f	width of the 3 layers (m)	∇T	temperature gradient $\left(\frac{K}{m}\right)$
k_c, k_b	thermal conductivity for Germanium and Silicon $\left(\frac{W}{m \cdot K}\right)$	ζ	form factor
Q	irradiance hitting the cell $\left(\frac{W}{m^2}\right)$		

14. Annex 3. Individually connected cells.

Analysis for the non-uniform irradiance scenario

The maximum power produced by the system occurs when the 48 cells work by themselves and produce energy without being connected with the others.

Microchannels cooling system

In table 24 this situation can be seen for the microchannels cooling system:

Table 24. Power generated when cells are not connected to each other for microchannels and non-uniform irradiance (W).

	1	2	3	4	5	6
1	16,16	19,22	19,68	19,47	17,17	9,33
2	28,85	34,05	34,46	33,39	30,37	18,62
3	34,37	38,86	38,56	38,66	39,43	25,30
4	29,10	38,68	37,71	37,16	37,72	28,03
5	33,52	37,04	36,52	36,84	37,20	28,90
6	30,53	35,44	35,31	35,83	36,03	26,20
7	22,70	28,48	29,59	29,89	28,58	20,79
8	7,16	10,80	11,57	10,99	9,67	7,94

The maximum power at this condition is: $\boldsymbol{Power = 1331.89\ W.}$

Microfluidic cells cooling system

In table 25 this situation can be seen for the microfluidic cells cooling system:

Table 25. Power generated when cells are not connected to each other for microfluidic cells and non-uniform irradiance (W).

	1	2	3	4	5	6
1	14,93	17,77	18,21	17,99	15,80	8,60
2	27,18	32,20	32,64	31,55	28,49	17,34
3	33,30	37,88	37,66	37,66	38,10	24,11
4	28,92	38,76	37,88	37,23	37,45	27,39
5	34,17	38,10	37,66	37,88	37,88	28,92
6	31,77	37,23	37,23	37,66	37,45	26,74
7	23,90	30,24	31,55	31,77	30,02	21,49
8	7,72	11,65	12,53	11,87	10,34	8,38

The maximum power under this conditions is: $\boldsymbol{Power = 1333.19\ W.}$

It can be seen how the most irradiated cell produces **451%** more energy than the less irradiated cell due to the non-uniform conditions.

Under these conditions, the microfluidic cells scenario produces **0.098%** more energy than the microchannels cooling system.

<u>Analysis for uniform irradiance scenario</u>

The maximum power produced by the system occurs when the 48 cells work by themselves and produce energy without being connected with the others.

Microchannels cooling system

In table 26 this situation can be seen for the microchannels cooling system:

Table 26. Power generated when cells are not connected to each other for microchannels and uniform irradiance (W).

	1	2	3	4	5	6
1	29,79	29,79	29,79	29,79	29,79	29,79
2	29,32	29,31	29,31	29,31	29,31	29,32
3	28,75	28,75	28,75	28,75	28,75	28,75
4	28,18	28,17	28,17	28,17	28,17	28,18
5	27,60	27,60	27,60	27,60	27,60	27,60
6	27,03	27,03	27,03	27,03	27,03	27,03
7	26,49	26,49	26,49	26,49	26,49	26,49
8	26,06	26,06	26,06	26,06	26,06	26,06

The maximum power under these conditions is: $\boldsymbol{Power = 1339.21\ W.}$

In this scenario the irradiance distribution is constant so the electrical power is only affected by the temperature differences. The coolest cell produces **14.3%** more energy than the hottest one.

Microfluidic cells cooling system

In table 27 this situation can be seen for the microchannels cooling system:

Table 27. Power generated when cells are not connected to each other for microfluidic cells and uniform irradiance (W).

	1	2	3	4	5	6
1	27,90	27,90	27,90	27,90	27,90	27,90
2	27,90	27,90	27,90	27,90	27,90	27,90
3	27,90	27,90	27,90	27,90	27,90	27,90
4	27,90	27,90	27,90	27,90	27,90	27,90
5	27,90	27,90	27,90	27,90	27,90	27,90
6	27,90	27,90	27,90	27,90	27,90	27,90
7	27,90	27,90	27,90	27,90	27,90	27,90
8	27,90	27,90	27,90	27,90	27,90	27,90

15. Annex 4. 48x1 configuration

Non-uniform irradiance distribution

Microchannels cooling system

The maximum power point has these parameters:

$$\boldsymbol{Power = 857.83\ W}$$

$$Current = 11.65\ A$$

$$Voltage = 73.61\ V$$

Under these conditions, the power generated by each cell can be seen in table 28:

Table 28. Power generated by the 48x1 configuration, microchannels and non-uniform irradiance (W).

	1	2	3	4	5	6
1	-5,83	-5,83	-5,83	-5,83	-5,83	-5,83
2	28,41	31,45	31,50	31,33	30,26	-5,83
3	31,02	31,45	31,38	31,45	31,71	-5,83
4	28,90	30,83	30,68	30,68	30,93	27,80
5	29,82	30,10	29,99	30,08	30,33	28,72
6	28,80	29,48	29,39	29,51	29,77	23,14
7	-5,83	27,79	28,12	28,26	27,98	-5,83
8	-5,83	-5,83	-5,83	-5,83	-5,83	-5,83

It can be seen that for the maximum power point there are 16 cells where the current is passing thorough the bypass diode that consumes energy. This means than this configuration with this conditions would produce more energy if this cells were not there.

In table 29 a comparison between the maximum electrical power output under these conditions and the 48x1 one is shown:

Table 29. Absolut difference between 48x1 and individually connected cells for microchannels and non-uniform irradiance (W).

	1	2	3	4	5	6
1	21,98	25,04	25,50	25,30	23,00	15,16
2	0,44	2,60	2,96	2,07	0,11	24,45
3	3,36	7,40	7,18	7,21	7,72	31,13
4	0,19	7,85	7,03	6,48	6,78	0,23
5	3,70	6,94	6,53	6,76	6,87	0,18
6	1,73	5,96	5,92	6,32	6,26	3,05
7	28,53	0,69	1,47	1,63	0,60	26,62
8	12,99	16,63	17,40	16,82	15,49	13,77

There is a big difference in the cells where the bypass diode is working. The cells that have nearly 0 W of error mean that the current that is passing through them is close to the current that produces the maximum power for that cell.

In the 48x1 configuration and under these conditions a **35.6%** less energy is produced than in the non-interconnected scenario.

Microfluidic cells cooling system

The calculated I-V and P-V curve can be seen in figure 31:

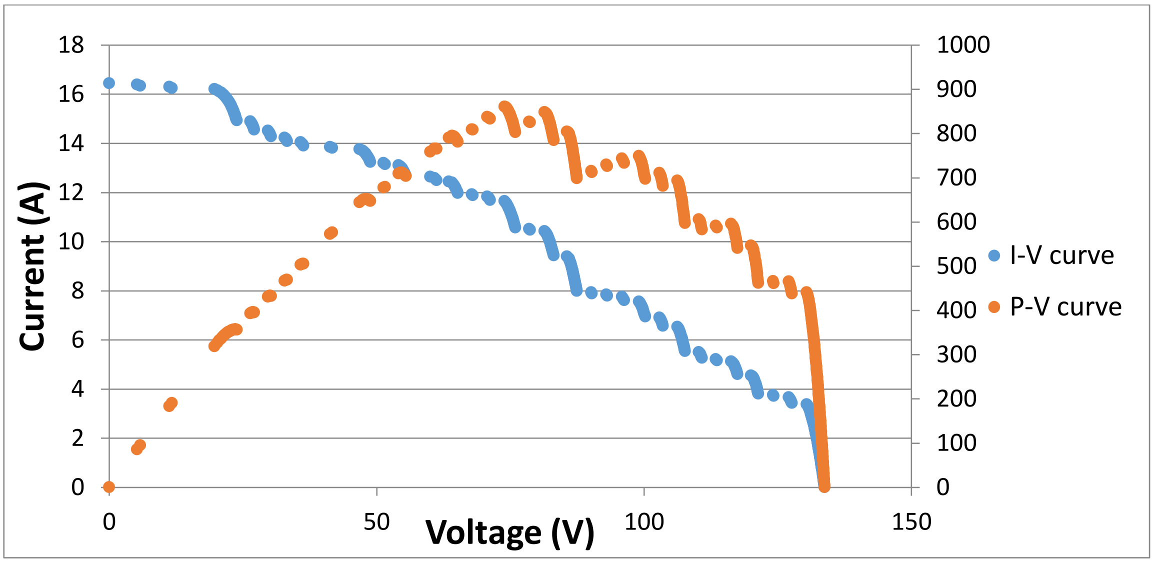


Figure 31. I-V and P-V curves for the 48x1 configuration for microfluidic cells and non-uniform irradiance,

The pattern is really similar to the microchannels cooling system one.

The maximum power generated by this configuration under the described conditions is:

$\boldsymbol{Power = 860.97\ W}$

$Current = 11.65\ A$

$Voltage = 73.88\ V$

Under these conditions, the power generated by each cell can be seen in table 30:

Table 30. Power generated by the 48x1 configuration, microfluidic cells and non-uniform irradiance (W).

	1	2	3	4	5	6
1	-5,83	-5,83	-5,83	-5,83	-5,83	-5,83
2	26,61	29,94	30,04	29,78	28,44	-5,83
3	30,17	30,79	30,77	30,77	30,82	-5,83
4	28,74	30,88	30,79	30,73	30,75	27,13
5	30,32	30,82	30,77	30,79	30,79	28,74
6	29,84	30,73	30,73	30,77	30,75	23,77
7	-5,83	29,36	29,78	29,84	29,28	-5,83
8	-5,83	-5,83	-5,83	-5,83	-5,83	-5,83

In table 31 a comparison between the maximum electrical power output under these conditions and the 48x1 one is shown:

Table 31. Absolut difference between 48x1 and individually connected cells for microfluidic cells and non-uniform irradiance (W).

	1	2	3	4	5	6
1	20,76	23,60	24,04	23,82	21,63	14,42
2	0,57	2,26	2,60	1,77	0,05	23,16
3	3,13	7,09	6,89	6,89	7,29	29,94
4	0,19	7,88	7,09	6,50	6,70	0,27
5	3,85	7,29	6,89	7,09	7,09	0,19
6	1,93	6,50	6,50	6,89	6,70	2,97
7	29,72	0,87	1,77	1,93	0,74	27,32
8	13,55	17,48	18,35	17,70	16,17	14,21

Again important power differences are found due to mismatch errors.

In the 48x1 configuration and under these conditions a **35.42%** less energy is produced than in the non-interconnected scenario.

In table 32 the differences between both cooling systems are presented:

Table 32. Power differences between the microfluidic cells and microchannels in 48x1 and non-uniform irradiance (W).

	1	2	3	4	5	6
1	0,00	0,00	0,00	0,00	0,00	0,00
2	-1,80	-1,51	-1,47	-1,55	-1,83	0,00
3	-0,85	-0,66	-0,61	-0,68	-0,90	0,00
4	-0,16	0,05	0,12	0,05	-0,18	-0,67
5	0,50	0,72	0,79	0,71	0,46	0,02
6	1,04	1,24	1,34	1,26	0,98	0,63
7	0,00	1,57	1,66	1,58	1,30	0,00
8	0,00	0,00	0,00	0,00	0,00	0,00

It can be seen how more energy is produced in the zones with less temperature. The microchannels cooling system makes the temperature grow gradually while the microfluidic cells has a specific temperature for each cell depending on the irradiation received.

Cooling system power comparison

Under these conditions, the system cooled with microfluidic cells produces **0.37%** more energy than cooled with microchannels.

The difference is so low because the temperature differences affect the open circuit voltage of the cell. In 48x1, all the cells share the same current but can have different voltages.

Uniform irradiance distribution

Microchannels cooling system

The calculated I-V and P-V curve can be seen in figure 32:

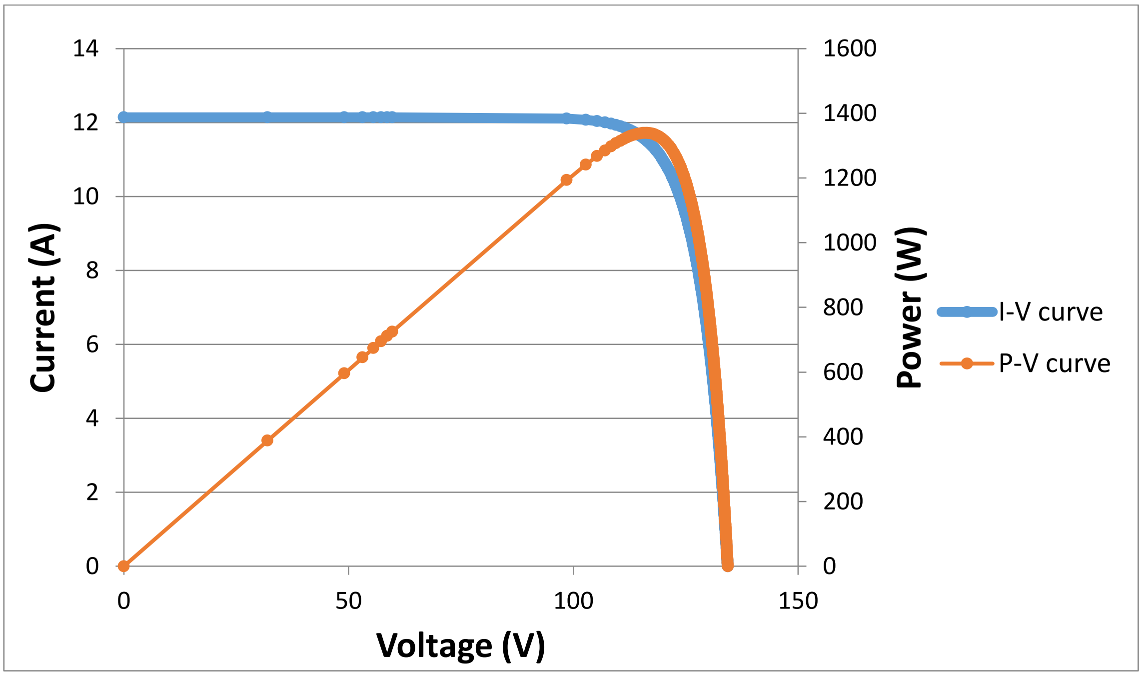


Figure 32. I-V and P-V curves for the 48x1 configuration for microchannels and uniform irradiance,

It can be seen how regular both curves are, the shape is the same that a single PV cell has. Now the irradiation is uniform the same all the cells so the behaviour is only affected by the temperature differences.

In this scenario any cell starts consuming energy so not a single bypass diode has to be used.

The maximum power generated by this configuration under the described conditions is:

$$\boldsymbol{Power = 1338.97\ W}$$

$$Current = 11.53\ A$$

$$Voltage = 116.12\ V$$

Under these conditions, the power generated by each cell can be seen in table 33:

Table 33. Power generated by the 48x1 configuration, microchannels and uniform irradiance (W).

	1	2	3	4	5	6
1	29,78	29,78	29,78	29,78	29,78	29,78
2	29,31	29,31	29,31	29,31	29,31	29,31
3	28,75	28,75	28,75	28,75	28,75	28,75
4	28,18	28,17	28,17	28,17	28,17	28,18
5	27,60	27,60	27,60	27,60	27,60	27,60
6	27,03	27,02	27,02	27,02	27,02	27,03
7	26,48	26,48	26,48	26,48	26,48	26,48
8	26,05	26,05	26,05	26,05	26,05	26,05

The cells that produce more energy are the ones that have the lowest temperature.

In table 34 a comparison between the maximum electrical power output under these conditions and the 48x1 one is shown:

Table 34. Absolut difference between 48x1 and individually connected cells for microfluidic cells and uniform irradiance (W).

	1	2	3	4	5	6
1	0,0109	0,0109	0,0109	0,0109	0,0109	0,0109
2	0,0062	0,0062	0,0062	0,0062	0,0062	0,0062
3	0,0023	0,0023	0,0023	0,0023	0,0023	0,0023
4	0,0002	0,0002	0,0002	0,0002	0,0002	0,0002
5	0,0003	0,0003	0,0003	0,0003	0,0003	0,0003
6	0,0024	0,0024	0,0024	0,0024	0,0024	0,0024
7	0,0063	0,0063	0,0063	0,0063	0,0063	0,0063
8	0,0107	0,0107	0,0107	0,0107	0,0107	0,0107

As it can be seen the difference is really low because once there is a uniform irradiance the temperature affects principally the voltage not the current.

In the 48x1 configuration and under these conditions **0.02%** less energy is produced than in the non-interconnected scenario. This is not a relevant result.

Microfluidic cells cooling system

The calculated I-V and P-V curve can be seen in figure 33:

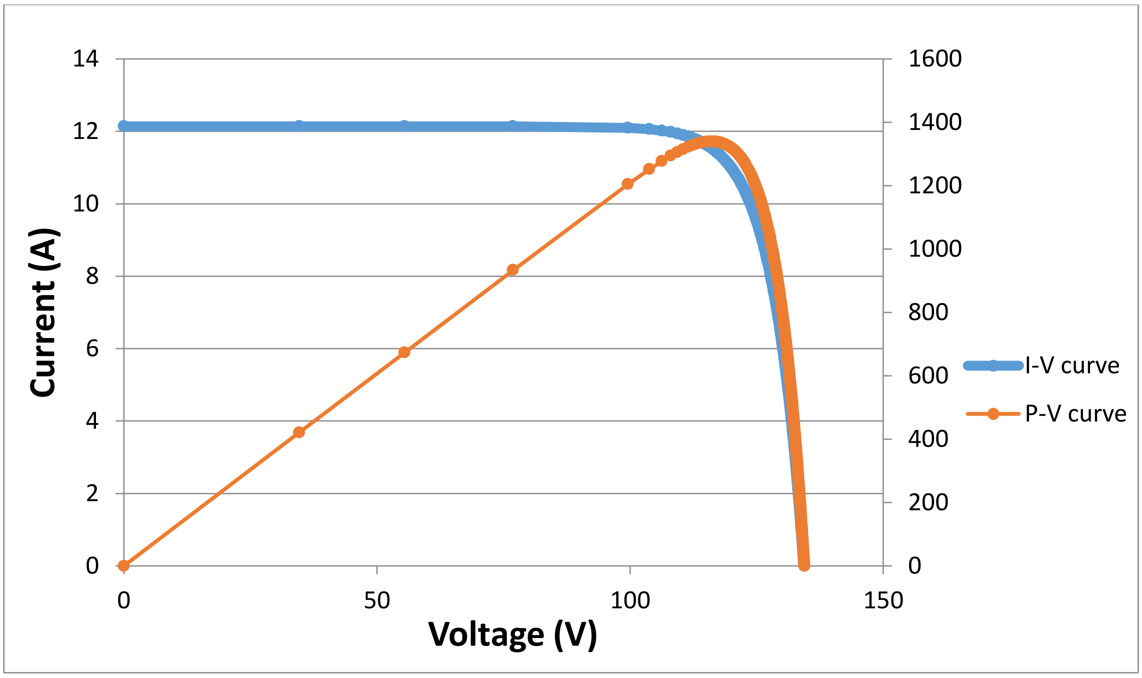


Figure 33. I-V and P-V curves for the 48x1 configuration for microfluidic cells and uniform irradiance,

The pattern is really similar to the microchannels cooling system one.

The maximum power generated by this configuration under the described conditions is:

$\boldsymbol{Power = 1339.15\,W}$

$Current = 11.53\,A$

$Voltage = 116.14\,V$

Under these conditions, the power generated by each cell can be seen in table 35:

Table 35. Power generated by the 48x1 configuration, microfluidic cells and uniform irradiance (W).

	1	2	3	4	5	6
1	27,90	27,90	27,90	27,90	27,90	27,90
2	27,90	27,90	27,90	27,90	27,90	27,90
3	27,90	27,90	27,90	27,90	27,90	27,90
4	27,90	27,90	27,90	27,90	27,90	27,90
5	27,90	27,90	27,90	27,90	27,90	27,90
6	27,90	27,90	27,90	27,90	27,90	27,90
7	27,90	27,90	27,90	27,90	27,90	27,90
8	27,90	27,90	27,90	27,90	27,90	27,90

The comparison between this scenario and the individually connected cells is not necessary because they have the same electrical power output.

In table 36 the differences between both cooling systems are presented:

Table 36. Power differences between the microfluidic cells and microchannels in 48x1 and uniform irradiance (W).

	1	2	3	4	5	6
1	-1,88	-1,88	-1,88	-1,88	-1,88	-1,88
2	-1,41	-1,41	-1,41	-1,41	-1,41	-1,41
3	-0,85	-0,85	-0,85	-0,85	-0,85	-0,85
4	-0,28	-0,28	-0,28	-0,28	-0,28	-0,28
5	0,30	0,30	0,30	0,30	0,30	0,30
6	0,87	0,88	0,88	0,88	0,88	0,87
7	1,42	1,42	1,42	1,42	1,42	1,42
8	1,85	1,85	1,85	1,85	1,85	1,85

Differences between the uniform and non-uniform irradiance

In the 48x1 configuration with microchannels, the uniform irradiance distribution produces **56.09%** more energy than the non-uniform irradiance distribution.

In the 48x1 scenario with microfluidic cells, the uniform irradiance distribution produces **55.54%** more energy than the non-uniform irradiance distribution.

16. Annex 5. 6x8 configuration

Non-uniform irradiance distribution

Microchannels cooling system

In the 6x8 configuration blocking diodes for the 8 parallel series haven't been considered so the maximum voltage has to be defined in order to avoid the creation of hotspots and the destruction of the cells. When fixing the intensity of every line to 0, the maximum voltage of each line can be found. In table 37 this can be seen:

Table 37. Maximum limiting voltage of the 6x8 configuration for microchannels and non-uniform irradiance.

	Voltage on each cell (V)							
	1	2	3	4	5	6	Vmax (V)	Current (A)
1	2,939	2,944	2,943	2,946	2,950	2,922	17,645	0
2	2,918	2,914	2,912	2,916	2,929	2,929	17,518	0
3	2,864	2,854	2,850	2,855	2,873	2,889	17,184	0
4	2,806	2,797	2,791	2,797	2,815	2,840	16,846	0
5	2,759	2,743	2,738	2,744	2,764	2,792	16,539	0
6	2,715	2,701	2,693	2,699	2,722	2,749	16,280	0
7	2,684	2,674	2,667	2,673	2,695	2,717	16,111	0
8	2,592	2,610	2,607	2,609	2,621	2,639	15,678	0

To protect the system the maximum voltage is 15.678 volts.

The calculated I-V and P-V curve can be seen in figure 34:

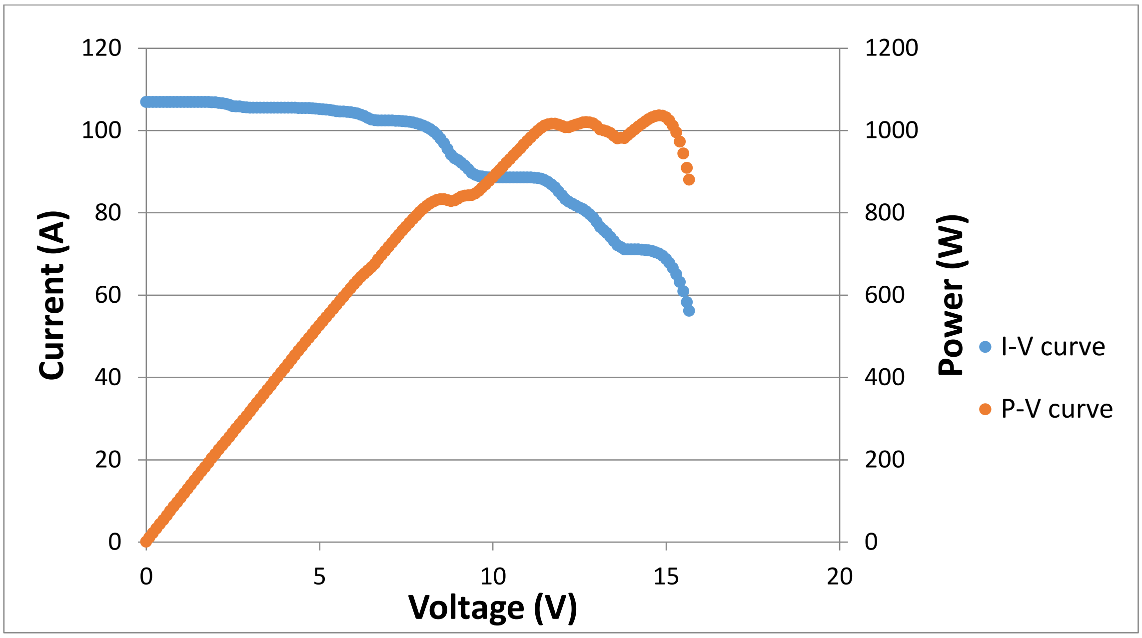


Figure 34. I-V and P-V curves for the 6x8 configuration for microchannels cells and non-uniform irradiance,

The maximum power generated by this configuration under the described conditions is:

$$\boldsymbol{Power = 1036.3\ W}$$

$$Current = 70.02\ A$$

$$Voltage = 14.8\ V$$

Under these conditions, the power generated by each cell can be seen in table 38:

Table 38. Power generated by the 6x8 configuration, microchannels and non-uniform irradiance (W).

	1	2	3	4	5	6
1	10,79	10,89	10,90	10,91	10,86	4,63
2	21,24	21,43	21,42	21,42	21,40	8,60
3	28,50	28,74	28,68	28,74	28,97	12,87
4	29,10	31,56	31,40	31,40	31,66	22,01
5	31,67	32,18	32,04	32,15	32,42	25,94
6	28,61	29,25	29,16	29,28	29,53	25,09
7	21,91	22,84	22,88	22,95	23,03	20,70
8	6,78	7,21	7,24	7,22	7,19	7,06

It can be seen how the most irradiated cells produce more energy than the rest and comparing it with the 48x1 configuration, there are no cells consuming energy.

In table 39 a comparison between the maximum electrical power output under these conditions and the 6x8 one is shown:

Table 39. Absolut difference between 6x8 and individually connected cells for microchannrls and non-uniform irradiance (W).

	1	2	3	4	5	6
1	5,37	8,32	8,78	8,56	6,31	4,70
2	7,61	12,62	13,04	11,97	8,97	10,02
3	5,88	10,12	9,88	9,92	10,47	12,43
4	0,00	7,12	6,31	5,77	6,06	6,02
5	1,85	4,87	4,48	4,69	4,78	2,96
6	1,92	6,19	6,15	6,55	6,49	1,11
7	0,79	5,64	6,71	6,93	5,55	0,09
8	0,38	3,59	4,34	3,77	2,48	0,88

There is an important difference in some cells located in the top part of the array. These mismatch losses are produced by the non-uniform irradiance in the series but also because the higher temperatures in the bottom limit the global voltage of the 8 series of the CPV array.

In the 6x8 configuration and under these conditions **22.19%** less energy is produced than in the non-interconnected scenario.

Microfluidic cells cooling system

As in the microchannels cooling system, the maximum voltage has to be limited. In table 40 this can be seen:

Table 40. Maximum limiting voltage of the 6x8 configuration for microfluidic cells and non-uniform irradiance.

	Voltage on each cell (V)							
	1	2	3	4	5	6	Vmax (V)	Inte (A)
1	2,771	2,778	2,779	2,778	2,773	2,748	16,627	0
2	2,792	2,796	2,797	2,796	2,793	2,777	16,751	0
3	2,797	2,801	2,801	2,801	2,801	2,788	16,788	0
4	2,793	2,801	2,801	2,800	2,800	2,792	16,788	0
5	2,798	2,801	2,801	2,801	2,801	2,793	16,794	0
6	2,796	2,800	2,800	2,801	2,800	2,791	16,789	0
7	2,788	2,795	2,796	2,796	2,794	2,784	16,753	0
8	2,743	2,761	2,764	2,762	2,756	2,747	16,534	0

To protect the system the maximum voltage is 16.534 volts.

The calculated I-V and P-V curve can be seen in figure 35:

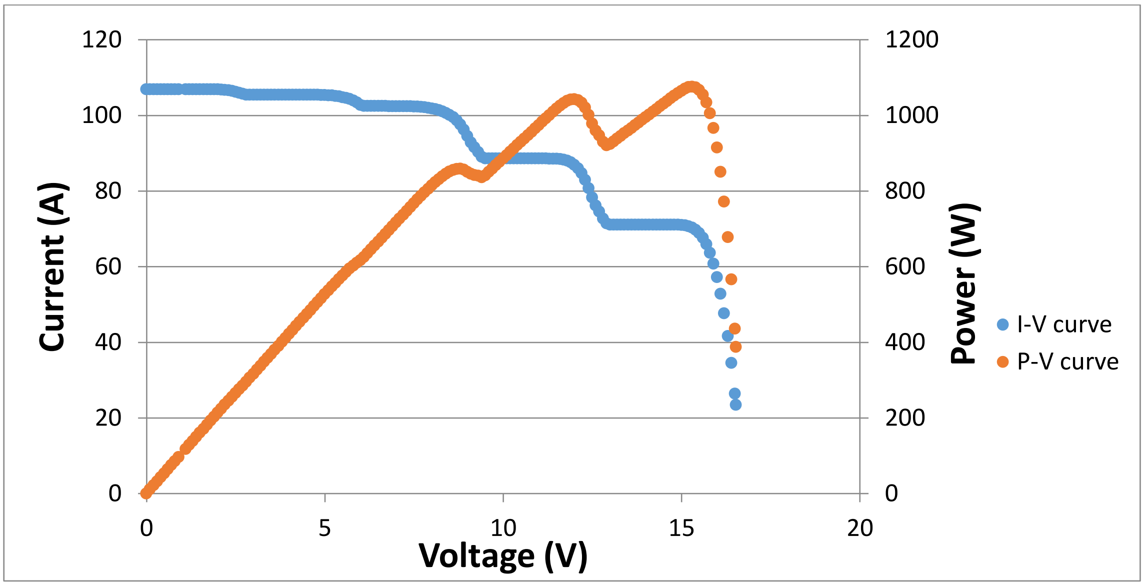


Figure 35. I-V and P-V curves for the 6x8 configuration for microfluidic cells and non-uniform irradiance,

The pattern is really similar to the microchannels cooling system one but with less irregularities due to the more uniform temperature distribution. All the big slopes correspond to situations where a cell starts consuming energy.

The maximum power generated by this configuration under the described conditions is:

$$\boldsymbol{Power = 1075.8\ W}$$

$$Current = 70.31\ A$$

$$Voltage = 15.3\ V$$

Under these conditions, the power generated by each cell can be seen in table 41:

Table 41. Power generated by the 6x8 configuration, microfluidic cells and non-uniform irradiance (W).

	1	2	3	4	5	6
1	10,11	10,23	10,24	10,24	10,16	7,12
2	20,21	20,48	20,50	20,45	20,30	14,27
3	27,70	28,10	28,08	28,08	28,11	20,98
4	28,81	31,08	30,99	30,92	30,94	26,86
5	31,93	32,63	32,57	32,60	32,60	28,08
6	29,71	30,58	30,58	30,62	30,60	25,24
7	23,32	24,54	24,66	24,68	24,52	20,60
8	7,68	8,74	8,79	8,75	8,61	8,20

In table 42 a comparison between the maximum electrical power output under these conditions and the 6x8 one is shown:

Table 42. Absolut difference between 6x8 and individually connected cells for microfluidic cells and non-uniform irradiance (W).

	1	2	3	4	5	6
1	4,82	7,54	7,97	7,75	5,65	1,47
2	6,96	11,72	12,14	11,10	8,19	3,07
3	5,60	9,78	9,58	9,58	9,99	3,13
4	0,11	7,68	6,89	6,31	6,50	0,54
5	2,24	5,47	5,10	5,29	5,29	0,84
6	2,05	6,65	6,65	7,04	6,84	1,50
7	0,58	5,70	6,89	7,09	5,50	0,89
8	0,05	2,92	3,73	3,12	1,73	0,18

The most affected cells are the ones in series 2 due to a cell that has half the irradiance of the others. In the 6x8 configuration and under these conditions a **19.31%** less energy is produced than in the non-interconnected scenario.

In table 43 the differences between both cooling systems are presented:

Table 43. Power differences between the microfluidic cells and microchannels in 6x8 and non-uniform irradiance (W).

	1	2	3	4	5	6
1	-0,68	-0,66	-0,66	-0,67	-0,71	2,49
2	-1,03	-0,95	-0,93	-0,97	-1,10	5,67
3	-0,80	-0,64	-0,60	-0,66	-0,85	8,11
4	-0,28	-0,48	-0,41	-0,48	-0,72	4,84
5	0,26	0,45	0,53	0,45	0,17	2,14
6	1,11	1,33	1,42	1,35	1,07	0,15
7	1,41	1,70	1,78	1,72	1,49	-0,10
8	0,90	1,52	1,56	1,53	1,43	1,14

The microchannels cooling system produces more energy in the top cells than the microfluidic cells one. Then, in the microchannels scenario the coolant warms up and the temperature of the cells at the bottom is higher so they produce less energy.

Cooling system power comparison

Under these conditions, the system cooled with microfluidic cells produces **3.81%** more energy than cooled with microchannels.

<u>Uniform irradiance distribution</u>

Microchannels cooling system

The maximum voltage has to be limited. In table 44 this can be seen:

Table 44. Maximum limiting voltage of the 6x8 configuration for microchannels and uniform irradiance.

	Voltage on each cell (V)							
	1	2	3	4	5	6	Vmax (V)	Current (A)
1	2,94	2,94	2,94	2,94	2,94	2,94	17,64	0
2	2,91	2,91	2,91	2,91	2,91	2,91	17,44	0
3	2,86	2,86	2,86	2,86	2,86	2,86	17,19	0
4	2,82	2,82	2,82	2,82	2,82	2,82	16,93	0
5	2,78	2,78	2,78	2,78	2,78	2,78	16,67	0
6	2,74	2,74	2,74	2,74	2,74	2,74	16,42	0
7	2,70	2,70	2,70	2,70	2,70	2,70	16,18	0
8	2,66	2,66	2,66	2,66	2,66	2,66	15,98	0

The calculated I-V and P-V curve can be seen in figure 36:

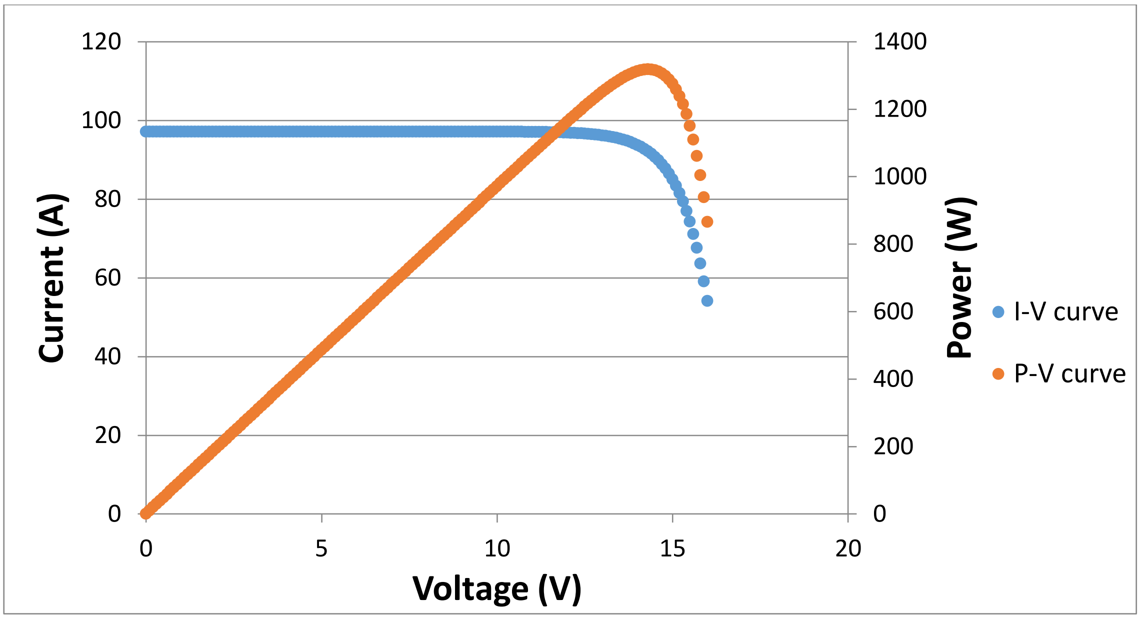


Figure 36. I-V and P-V curves for the 6x8 configuration for microchannels and uniform irradiance,

The maximum power generated by this configuration under the described conditions is:

$$\boldsymbol{Power = 1317.42\ W}$$

$$Current = 92.13\ A$$

$Voltage = 14.3\,V$

Under these conditions, the power generated by each cell can be seen in table 45:

Table 45. Power generated by the 6x8 configuration, microchannels and uniform irradiance (W).

	1	2	3	4	5	6
1	28,66	28,65	28,65	28,65	28,65	28,66
2	28,54	28,54	28,53	28,53	28,54	28,54
3	28,33	28,33	28,33	28,33	28,33	28,33
4	28,03	28,03	28,03	28,03	28,03	28,03
5	27,59	27,59	27,59	27,59	27,59	27,59
6	26,97	26,97	26,97	26,97	26,97	26,97
7	26,15	26,15	26,15	26,15	26,15	26,15
8	25,31	25,30	25,30	25,30	25,30	25,31

The cells that produce more energy are the ones that have the lowest temperature, on the top.

In table 46 a comparison between the maximum electrical power output under these conditions and the 6x8 one is shown:

Table 46. Absolut difference between 6x8 and individually connected cells for microchannels and uniform irradiance (W).

	1	2	3	4	5	6
1	1,13	1,13	1,13	1,13	1,13	1,13
2	0,78	0,78	0,78	0,78	0,78	0,78
3	0,42	0,42	0,42	0,42	0,42	0,42
4	0,15	0,15	0,15	0,15	0,15	0,15
5	0,01	0,01	0,01	0,01	0,01	0,01
6	0,06	0,06	0,06	0,06	0,06	0,06
7	0,33	0,33	0,33	0,33	0,33	0,33
8	0,76	0,76	0,76	0,76	0,76	0,76

In the 6x8 configuration and under these conditions **1.63%** less energy is produced than in the non-interconnected scenario.

Microfluidic cells cooling system

Due to the uniformity of temperature and irradiance, there is no limiting voltage because all the series produce the same energy.

The calculated I-V and P-V curve can be seen in figure 37:

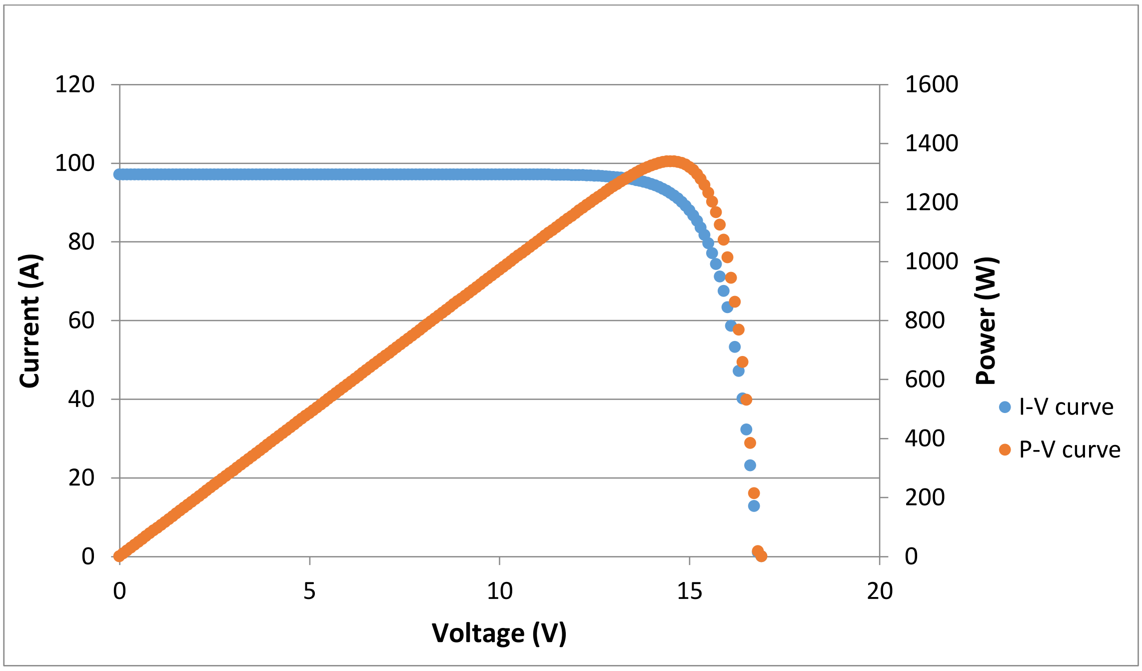


Figure 37. I-V and P-V curves for the 6x8 configuration for microfluidic cells and uniform irradiance,

The maximum power generated by this configuration under the described conditions is:

$\boldsymbol{Power = 1339.15\ W}$

$Current = 92.35\ A$

$Voltage = 14.5\ V$

Under these conditions, the power generated by each cell can be seen in table 47:

Table 47. Power generated by the 6x8 configuration, microfluidic cells and uniform irradiance (W).

	1	2	3	4	5	6
1	27,90	27,90	27,90	27,90	27,90	27,90
2	27,90	27,90	27,90	27,90	27,90	27,90
3	27,90	27,90	27,90	27,90	27,90	27,90
4	27,90	27,90	27,90	27,90	27,90	27,90
5	27,90	27,90	27,90	27,90	27,90	27,90
6	27,90	27,90	27,90	27,90	27,90	27,90
7	27,90	27,90	27,90	27,90	27,90	27,90
8	27,90	27,90	27,90	27,90	27,90	27,90

The comparison between this scenario and the individually connected cells is not necessary because they have the same electrical power output.

In table 48 the differences between both cooling systems are presented:

Table 48. Power differences between the microfluidic cells and microchannels in 6x8 and uniform irradiance (W).

	1	2	3	4	5	6
1	-0,76	-0,76	-0,76	-0,76	-0,76	-0,76
2	-0,64	-0,64	-0,64	-0,64	-0,64	-0,64
3	-0,44	-0,43	-0,43	-0,43	-0,43	-0,44
4	-0,13	-0,13	-0,13	-0,13	-0,13	-0,13
5	0,31	0,31	0,31	0,31	0,31	0,31
6	0,93	0,93	0,93	0,93	0,93	0,93
7	1,74	1,75	1,75	1,75	1,75	1,74
8	2,59	2,60	2,60	2,60	2,60	2,59

The results are similar to the 48x1. The microchannels temperature distribution makes the top cells produce more energy. At the bottom is the opposite.

Cooling system power comparison

Under these conditions, the system cooled with microfluidic cells produces **1.65%** more energy than cooled with microchannels.

Differences between the uniform and non-uniform irradiance

In the 6x8 configuration with microchannels, the uniform irradiance distribution produces **27.13%** more energy than the non-uniform irradiance distribution.

In the 6x8 configuration with microfluidic cells, the uniform irradiance distribution produces **22.46%** more energy than the non-uniform irradiance distribution.

The non-uniform irradiance distribution has more effect under these conditions.

17. Annex 6. 1x48 configuration

Non-uniform irradiance distribution

Microchannels cooling system

Limiting voltage of the system is the maximum voltage that makes all the cells work in good conditions:

Table 49. Maximum voltage of the 1x48 configuration for microchannels and non-uniform irradiance.

	Current ton each cell (A)						
	1	2	3	4	5	6	**Vmax (V)**
1	6,23	7,41	7,59	7,51	6,62	3,59	2,59
2	11,08	13,06	13,20	12,81	11,68	7,17	
3	12,88	14,43	14,27	14,37	14,84	9,63	
4	10,27	13,41	12,94	12,88	13,45	10,31	
5	10,72	11,28	10,91	11,23	12,02	9,97	
6	8,36	8,95	8,53	8,98	10,12	8,19	
7	5,21	6,00	5,81	6,24	7,04	5,80	
8	0,00	0,63	0,56	0,62	0,91	1,13	

The maximum power generated by this configuration under the described conditions is:

$$\boldsymbol{Power = 1309.9\ W}$$

$$Current = 551.96\ A$$

$$Voltage = 2.37\ V$$

Under these conditions, the power generated by each cell can be seen in table 50:

Table 50. Power generated by the 1x48 configuration, microchannels and non-uniform irradiance (W)

	1	2	3	4	5	6
1	15,44	18,35	18,80	18,58	16,35	8,95
2	27,88	32,97	33,41	32,31	29,24	17,88
3	33,81	38,35	38,09	38,14	38,72	24,67
4	28,98	38,59	37,65	37,08	37,53	27,73
5	33,52	37,02	36,48	36,81	37,20	28,84
6	30,40	35,13	34,92	35,50	35,90	26,19
7	22,41	27,96	28,92	29,32	28,31	20,73
8	6,61	10,15	10,83	10,32	9,21	7,69

It can be seen how the most irradiated cells produce more energy than the rest.

In table 51 a comparison between the maximum electrical power output under these conditions and the 1x48 one is shown:

Table 51. Absolut difference between 1x48 and individually connected cells for microchannels and non-uniform irradiance (W).

	1	2	3	4	5	6
1	0,71	0,87	0,88	0,89	0,82	0,38
2	0,97	1,08	1,06	1,08	1,13	0,74
3	0,56	0,51	0,47	0,52	0,71	0,63
4	0,12	0,09	0,06	0,08	0,19	0,31
5	0,00	0,03	0,04	0,03	0,00	0,06
6	0,13	0,31	0,39	0,33	0,13	0,00
7	0,29	0,52	0,66	0,57	0,27	0,06
8	0,55	0,65	0,74	0,67	0,46	0,25

The maximum power output makes the central cells produce the maximum quantity of energy because those are the most irradiated.

In the 1x48 configuration and under these conditions **1.65%** less energy is produced than in the non-interconnected scenario.

Microfluidic cells cooling system

Limiting voltage of the system is the maximum voltage that makes all the cells work in good conditions:

Table 52. Maximum voltage of the 1x48 configuration for microfluidic cells and non-uniform irradiance.

	Curren ton each cell (A)						
	1	2	3	4	5	6	**Vmax**
1	1,33	1,88	1,97	1,93	1,50	0,15	2,74
2	3,76	4,78	4,87	4,65	4,03	1,80	
3	5,00	5,94	5,90	5,90	5,98	3,14	
4	4,11	6,12	5,94	5,81	5,85	3,80	
5	5,18	5,98	5,90	5,94	5,94	4,11	
6	4,69	5,81	5,81	5,90	5,85	3,67	
7	3,10	4,38	4,65	4,69	4,34	2,62	
8	0,00	0,71	0,87	0,75	0,47	0,11	

The calculated I-V and P-V curve can be seen in figure 38:

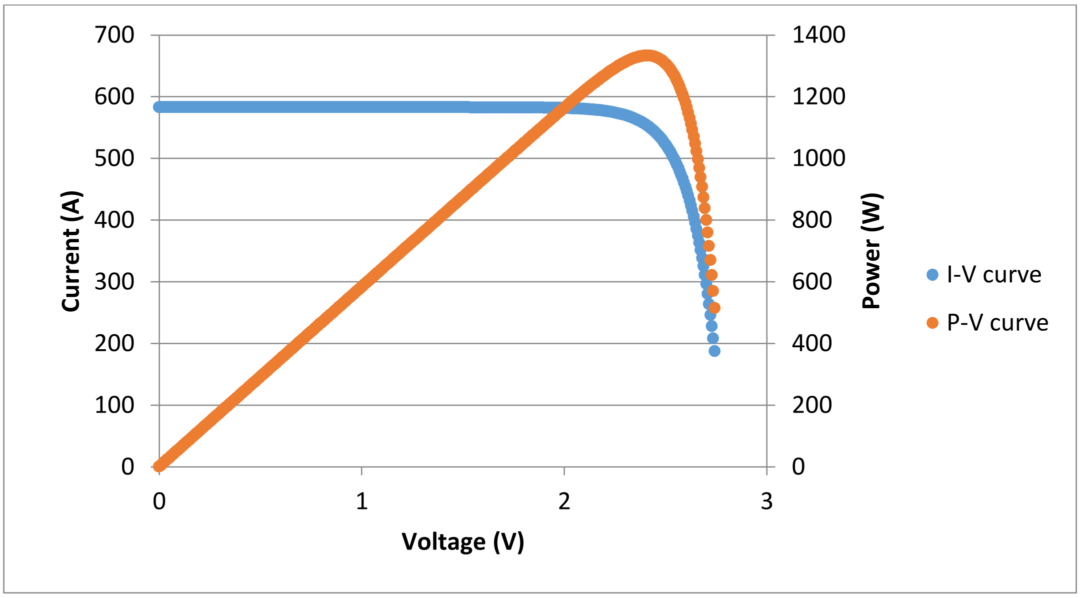


Figure 38. I-V and P-V curves for the 1x48 configuration for microfluidic cells and non-uniform irradiance,

The maximum power generated by this configuration under the described conditions is:

$$\boldsymbol{Power = 1333.04\ W}$$

$$Current = 553.17\ A$$

$$Voltage = 2.41\ V$$

Under these conditions, the power generated by each cell can be seen in table 53:

Table 53. Power generated by the 1x48 configuration, microfluidic cells and non-uniform irradiance (W).

	1	2	3	4	5	6
1	14,92	17,77	18,21	17,99	15,80	8,58
2	27,18	32,20	32,64	31,55	28,49	17,33
3	33,29	37,88	37,66	37,66	38,10	24,11
4	28,92	38,75	37,88	37,23	37,44	27,39
5	34,17	38,10	37,66	37,88	37,88	28,92
6	31,77	37,23	37,23	37,66	37,44	26,74
7	23,90	30,24	31,55	31,77	30,02	21,49
8	7,70	11,64	12,52	11,86	10,33	8,36

The comparison with the non-connected cells is not necessary because it's almost the same power.

In table 54 the differences between both cooling systems are presented:

Table 54. Power differences between the microfluidic cells and microchannels in 1x48 and non-uniform irradiance (W).

	1	2	3	4	5	6
1	-0,517	-0,582	-0,590	-0,590	-0,549	-0,369
2	-0,701	-0,773	-0,768	-0,768	-0,758	-0,549
3	-0,520	-0,467	-0,432	-0,477	-0,620	-0,556
4	-0,057	0,162	0,231	0,147	-0,085	-0,333
5	0,648	1,082	1,186	1,069	0,679	0,082
6	1,370	2,095	2,309	2,161	1,542	0,545
7	1,485	2,275	2,622	2,444	1,707	0,759
8	1,091	1,491	1,687	1,539	1,120	0,671

The microchannels cooling system produces more energy in the top cells than the microfluidic cells one. Then, in the microchannels scenario the coolant warms up and the temperature of the cells at the bottom is higher so they produce less energy.

Cooling system power comparison

Under these conditions, the system cooled with microfluidic cells produces **1.7%** more energy than cooled with microchannels.

Uniform irradiance distribution

Microchannels cooling system

Limiting voltage of the system is the maximum voltage that makes all the cells work in good conditions:

Table 55. Maximum limiting voltage of the 1x48 configuration for microchannels and uniform irradiance.

	Curren ton each cell (A)						
	1	2	3	4	5	6	**Vmax**
1	10,94	10,94	10,94	10,94	10,94	10,94	2,66
2	10,48	10,48	10,48	10,48	10,48	10,48	
3	9,74	9,73	9,73	9,73	9,73	9,74	
4	8,66	8,66	8,66	8,66	8,66	8,66	
5	7,17	7,17	7,17	7,17	7,17	7,17	
6	5,16	5,15	5,15	5,15	5,15	5,16	
7	2,60	2,59	2,58	2,58	2,59	2,60	
8	0,03	0,00	0,00	0,00	0,00	0,03	

The calculated I-V and P-V curve can be seen in figure 39:

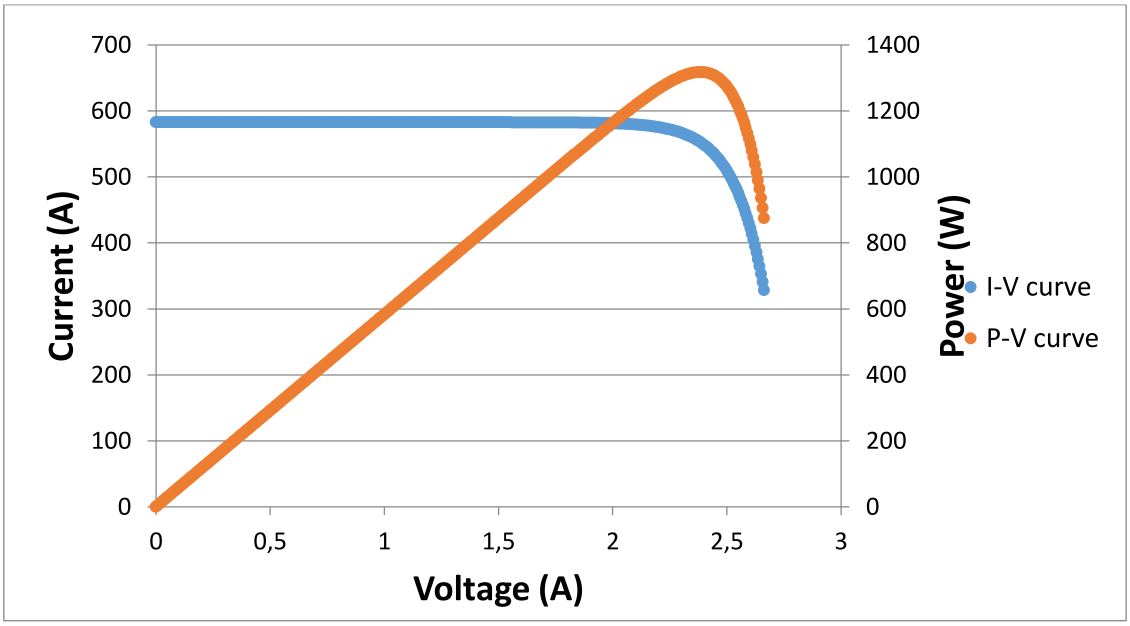


Figure 39. I-V and P-V curves for the 1x48 configuration for microchannels and uniform irradiance,

The maximum power generated by this configuration under the described conditions is:

$$\boldsymbol{Power = 1317.43\ W}$$

$$Current = 552.27\ A$$

$$Voltage = 2.39\ V$$

Under these conditions, the power generated by each cell can be seen in table 56:

Table 56. Power generated by the 1x48 configuration, microchannels and uniform irradiance (W).

	1	2	3	4	5	6
1	28,68	28,68	28,68	28,68	28,68	28,68
2	28,56	28,55	28,55	28,55	28,55	28,56
3	28,35	28,35	28,35	28,35	28,35	28,35
4	28,04	28,04	28,04	28,04	28,04	28,04
5	27,59	27,59	27,59	27,59	27,59	27,59
6	26,96	26,96	26,96	26,96	26,96	26,96
7	26,13	26,13	26,13	26,13	26,13	26,13
8	25,27	25,27	25,27	25,27	25,27	25,27

The cells that produce more energy are the ones that have the lowest temperature, on the top.

In table 57 a comparison between the maximum electrical power output under these conditions and the 1x48 one is shown:

Table 57. Absolut difference between 1x48 and individually connected cells for microchannels and uniform irradiance (W).

	1	2	3	4	5	6
1	1,11	1,11	1,11	1,11	1,11	1,11
2	0,76	0,76	0,76	0,76	0,76	0,76
3	0,40	0,40	0,40	0,40	0,40	0,40
4	0,14	0,14	0,14	0,14	0,14	0,14
5	0,01	0,01	0,00	0,00	0,01	0,01
6	0,06	0,06	0,07	0,07	0,06	0,06
7	0,35	0,36	0,36	0,36	0,36	0,35
8	0,79	0,79	0,80	0,80	0,79	0,79

In the 6x8 configuration and under these conditions **1.63%** less energy is produced than in the non-interconnected scenario.

Microfluidic cells cooling system

Due to the uniformity of temperature and irradiance, there is no limiting voltage because all the series produce the same energy.

The calculated I-V and P-V curve can be seen in figure 40:

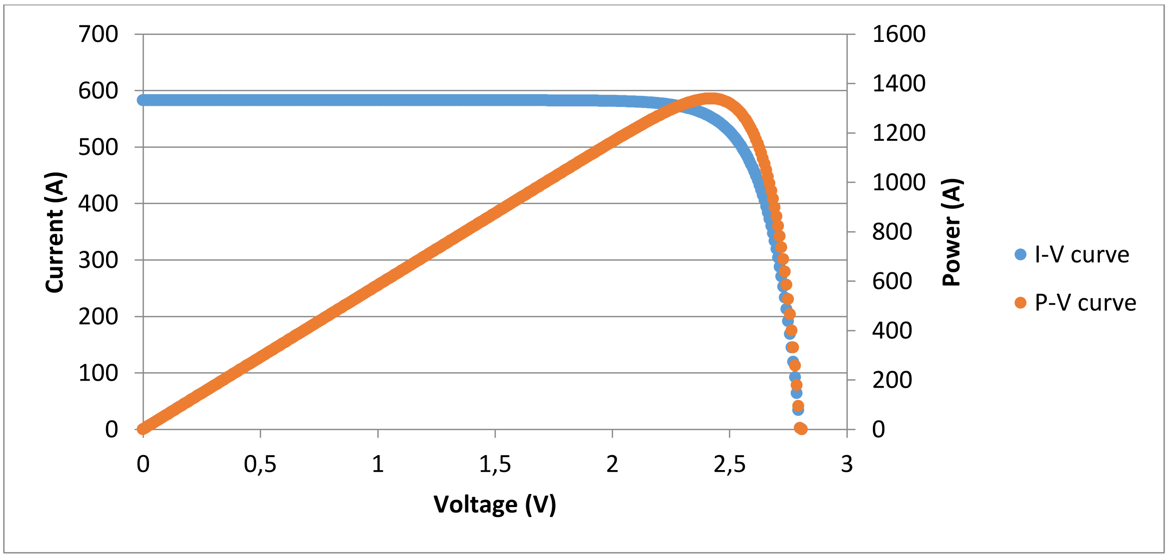


Figure 40. I-V and P-V curves for the 1x48 configuration for microfluidic cells and uniform irradiance,

The maximum power generated by this configuration under the described conditions is:

$\boldsymbol{Power = 1339.15\ W}$

$Current = 553.47\ A$

$Voltage = 2.42\ V$

Under these conditions, the power generated by each cell can be seen in table 58:

Table 58. Power generated by the 1x48 configuration, microfluidic cells and uniform irradiance (W).

	1	2	3	4	5	6
1	27,90	27,90	27,90	27,90	27,90	27,90
2	27,90	27,90	27,90	27,90	27,90	27,90
3	27,90	27,90	27,90	27,90	27,90	27,90
4	27,90	27,90	27,90	27,90	27,90	27,90
5	27,90	27,90	27,90	27,90	27,90	27,90
6	27,90	27,90	27,90	27,90	27,90	27,90
7	27,90	27,90	27,90	27,90	27,90	27,90
8	27,90	27,90	27,90	27,90	27,90	27,90

The comparison between this scenario and the individually connected cells is not necessary because they have the same electrical power output.

In table 59 the differences between both cooling systems are presented:

Table 59, Power differences between the microfluidic cells and microchannels in 1x48 and uniform irradiance (W).

	1	2	3	4	5	6
1	-0,78	-0,78	-0,78	-0,78	-0,78	-0,78
2	-0,66	-0,65	-0,65	-0,65	-0,65	-0,66
3	-0,45	-0,45	-0,45	-0,45	-0,45	-0,45
4	-0,14	-0,14	-0,14	-0,14	-0,14	-0,14
5	0,31	0,31	0,31	0,31	0,31	0,31
6	0,94	0,94	0,94	0,94	0,94	0,94
7	1,77	1,77	1,77	1,77	1,77	1,77
8	2,63	2,63	2,63	2,63	2,63	2,63

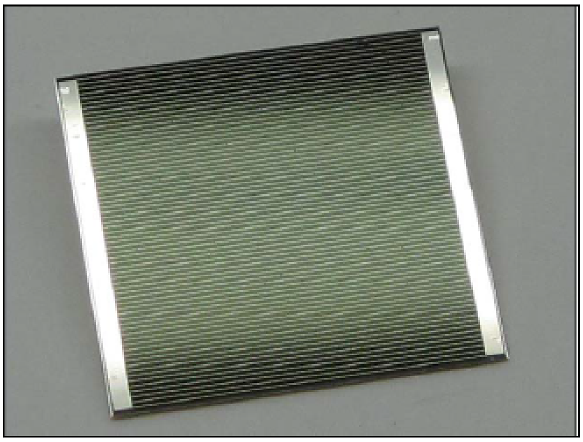
18. Annex 7

SPECTROLAB A BOEING COMPANY

CPV Point Focus Solar Cells

C4MJ Metamorphic Fourth Generation CPV Technology

- ✓*First 40% production cell*
- ✓*First fully qualified metamorphic cell*



Product Description

Typical Efficiency 40%

Recommended operating temperature <110°C

Epitaxial Structure

Triple junction solar cell on Germanium substrate

GaInP (1.82 eV) / GaInAs (1.33 eV) / Ge (0.66 eV)

Metallization

•Silver metallization on front busbar and grid fingers (optional gold flash finish)

•Silver metallization with 500Å gold on back surface

CPV Cell Ordering Guide

PP –MMMMMM– CCC

Mask Identifier

Packaging Format

11 – Processed Wafer

21 – Bare Cell in Waffle Tray

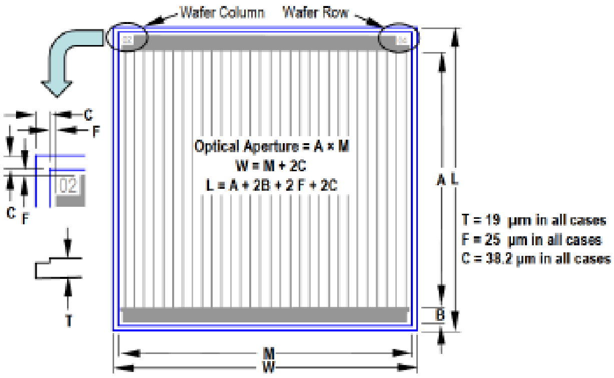
Configuration Options

401 – C4MJ, Silver front contact finish, 100% Tested

411 – C4MJ, Gold front contact finish, 100% Tested

Example: 21 – 046191 – 411 Bare Cell in Waffle Tray – 9.99×9.95mm Aperture -- C4MJ Gold Front Contact, 100% Tested

Mechanical Dimensions



Product	Aperture Area	Aperture Dimensions (mm)		Busbar (µm)
CPV Cell #	(mm ²)	M	A	B
PP- 046191 – CCC "CDO-100"	99.00	10.000	9.900	400 µm
PP- 046167 – CCC "CDO-086"	86.47	9.299	9.299	252 µm
PP- 046192 – CCC "CDO-076"	76.50	8.854	8.640	300 µm
PP- 046193 – CCC "CDO-030 "	30.74	5.547	5.542	300 µm

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ENVIRONMENTAL MANAGEMENT SYSTEM CERTIFIED BY DNV ISO 14001

AS9100 REGISTERED

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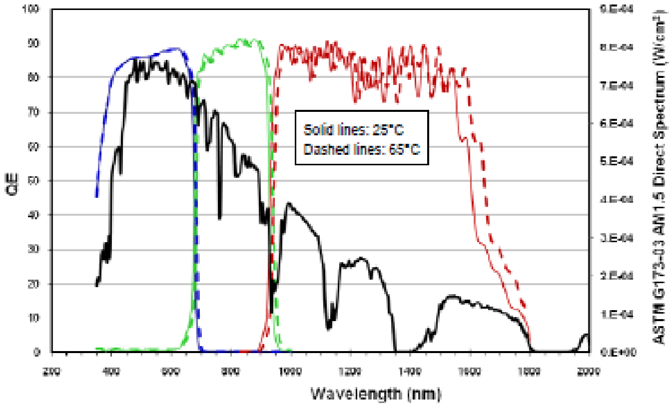
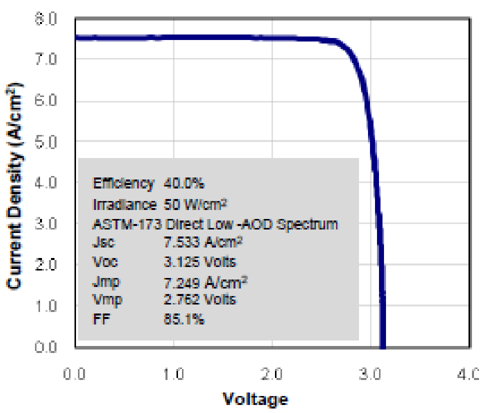
Spectral Response



Typical Current-Voltage Characteristics



Typical Performance Over Temperature

Temperature coefficient of efficiency: < –0.06%/°C

Qualification Tests Completed

Full Qualification Report is available on request (May 2011)

Test	Conditions	Requirement	Results
Performance	50 W/cm^2	Effmp > 37.6% target avg = 40.0%	Avg = 39.8%
Thermal Cycle	1500 cycles, -40°C to +110°C with 10 m dwell	unprotected cell < 2% degradation	NEff = 1.0
Unprotected Cell Damp Heat	1000 hrs, 85°C/85% RH	characterization	NEff > 0.98
High Temperature Soak	Unbiased soak at 180° C, 200°C, 225°C and 250°C	< 0.5% degradation after 25 year lifetime	NEff = 1.0
Outdoor Field Trial	> 10 kW on sun for 6 months	characterization	> 10 kW total
High Temperature Reverse Bias	-0.8V and -1.6V @ 140° C until failure	characterization	Complete
HTOL	1 A & 4 A dark forward bias at 160°C	characterization	NEff > 0.99
ESD	HBM 4000 V, CDM 2000 V	characterization	NEff = 1.0

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