Report: 30.3734.0-01

COMPARATIVE PHOTOVOLTAIC PERFORMANCE TESTS PVT COLLECTOR vs. PV MODULE

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1 EXECUTIVE SUMMARY

1.1 PRELIMINARY

This report is compiled according to the conditions laid in the offer No. 30.3734.0 presented to **FEGEN SOLAR LLC**, dated 12/03/2020.

1.2 OBJECT & SCOPE

The purpose of this report is to present the results of the comparison between the electrical performance of an individual PV module and the same type of module as being part of a PVT collector for a full day. This test has been done at two different tilt angles (5º and 35º). From the point of view of photovoltaic performance, both devices have been operating at their maximum power point system conditions (MPPT) during the test period. The PVT collector has been operated with a water flow across the heat exchanger for the duration of the tests.

The results presented in this report relate only to tested samples with serial numbers listed in section 2.1 SAMPLES DESCRIPTION.

1.3 CONCLUSIONS

The main conclusions that we can observe in this study are following exposed:

- The PV modules (individual and part of the PVT collector) have been characterized through measurement of the I –V curve and electroluminescence in order to check that if the devices suffer any damage during the exposure.
  The initial measured P_{MAX} values at STC of the samples are 292.1W ± 2.2% (PVT collector) and 292.2W ± 2.2% (standard PV module). Only low importance defects are observed in the EL images.
  No changes are observed after the exposure (P_{MAX} variations of +0.1% and -0.2%, and no changes in the EL images).
- The module on the PVT collector shows low-importance cracks in 2 central cells, and a scratch in other. Although there is no affection in the peak power of the PVT collector, the presence of these cracks could become a serious problem if their evolution with time and exposure makes them increase. The manufacturing process of the PVT collector has to be very careful because the backsheet and cells of the PV module are very sensitive to mechanical stresses.
- In the period of time free of shading effects, behavior of the PVT collector (PR and Efficiency) is better than PV module in average values of energy generated in all cases for 5º and 35º of tilt angle. This result is consistent with the fact that the PVT collector

has a lower operating temperature than PV module, which results in lower temperature losses and therefore a better PR.

- For the considered time period of testing, tilt angle of 5º presents a higher value of irradiation and generated energy than 35º. This fact probably will change in different time of periods along the year. These measurements will be performed three times more (in summer, in autumn and in winter).

2 TECHNICAL REPORT

2.1 SAMPLES DESCRIPTION

<table>
<tr><th colspan="4">REFERENCE DATA</th></tr>
<tr><td colspan="2">Number of samples</td><td colspan="2">2</td></tr>
<tr><td colspan="2">Reception date of samples</td><td colspan="2">25/05/2020</td></tr>
<tr><td colspan="2">Test period</td><td colspan="2">26/05/2020 – 05/06/2020</td></tr>
<tr><th colspan="4">TESTED SAMPLES DESCRIPTION</th></tr>
<tr><td>INTERNAL CODE</td><td>MANUFACTURER</td><td>MODEL</td><td>SERIAL NUMBER</td></tr>
<tr><td rowspan="2">30.3734.0-001</td><td rowspan="2">CANADIAN SOLAR
&
FEGEN</td><td>CS6K-295MS
(PV MODULE)</td><td>11810481170589</td></tr>
<tr><td>P-FHE16PS
(THERMAL COLLECTOR)</td><td>100122190621</td></tr>
<tr><td>30.3734.0-003</td><td>CANADIAN SOLAR</td><td>CS6K-295MS</td><td>11810481170711</td></tr>
</table>

<table>
<tr><th colspan="3">ELECTRICAL CHARACTERISTICS</th></tr>
<tr><td>MODEL</td><td>CS6K-295MS
30.3734.0-001</td><td>CS6K-295MS
30.3734.0-003</td></tr>
<tr><td>TYPE OF MODEL</td><td>PV thermal module</td><td>Standard PV module</td></tr>
<tr><td>Maximum power (P_{MP}) ....:</td><td colspan="2">295 W</td></tr>
<tr><td>Short-circuit current (I_{SC}) ....:</td><td colspan="2">9.75 A</td></tr>
<tr><td>Open-circuit voltage (V_{OC}) ....:</td><td colspan="2">39.5V</td></tr>
<tr><td>Current at maximum power (I_{MP}) ....:</td><td colspan="2">9.14 A</td></tr>
<tr><td>Voltage at maximum power (V_{MP}) ....:</td><td colspan="2">32.3 V</td></tr>
<tr><td>Maximum voltage system ....:</td><td colspan="2">1000 V</td></tr>
<tr><td>Short-circuit current temperature coefficient (α)[1] .....:</td><td colspan="2">5.17 mA/ºC</td></tr>
<tr><td>Open-circuit voltage temperature coefficient (β)[1] .....:</td><td colspan="2">-118.5 mV/ºC</td></tr>
<tr><td>Maximum power temperature coefficient (γ) ....:</td><td colspan="2">-1150 mW/ºC</td></tr>
<tr><td>Maximum over-current protection rating ....:</td><td colspan="2">15 A</td></tr>
<tr><td colspan="3">1) The short-circuit current temperature coefficient (α) and the open-circuit voltage coefficient (β) used in the performance at STC test have been obtained from the manufacturer datasheet. They can affect the validity of the results</td></tr>
</table>

CONSTRUCTIVE CHARACTERISTICS		
CELL CHARACTERISTICS		
Cell type reference ....:	Monocrystalline cells	
Cell dimensions ....:	156 mm x 156 mm	
MATERIALS		
Front cover ....:	3.2 mm tempered glass	
Rear cover ....:	Thermal collector	Standard substrate
Frame ....:	Anodized aluminium alloy	
COMPONENTS IDENTIFICATION		
Junction box ....:	IP67 3 diodes	
Cable ....:	4 mm^2 & 12 AWG	
Connector ....:	T4	
MODULE DESIGN – DIMENSIONS		
Module dimensions (width x length x height) ....:	1650 mm x 992 mm x 40 mm	
Module area ....:	1.64 m^2	
Weight ....:	22.2 kg	18.2 kg
MODULE DESIGN – ELECTRICAL CONFIGURATION		
Total number of cells ....:	60	
Serial/parallel connection of cells ....:	60/1	
Cells per bypass diode ....:	20	
No. of bypass diodes...:	3	

Tabla 1 Description of tested samples. Information obtained externally (not verified by CENER).

Figure 1 Marking CS6K-295MS model (standard module)

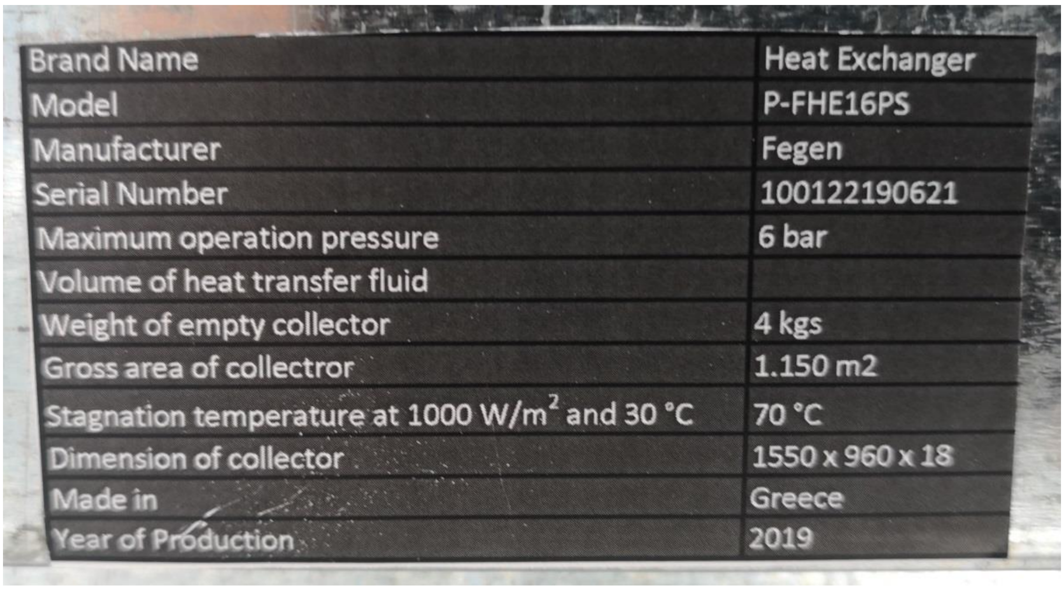


Figure 2 PVT marking

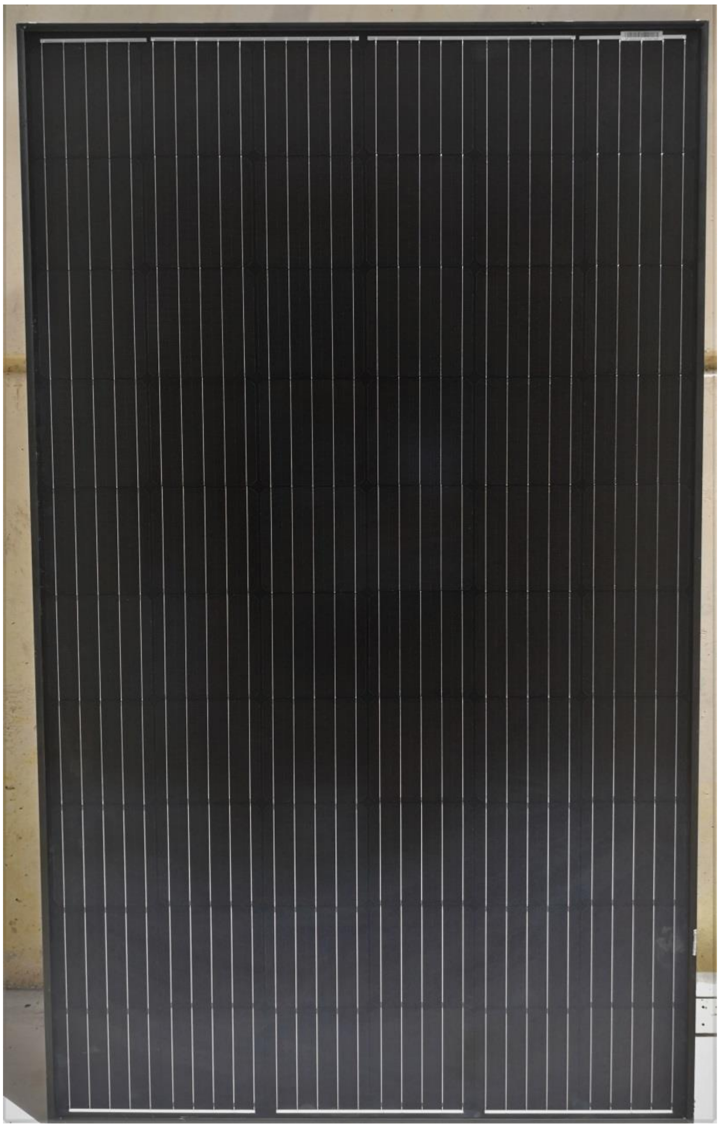


Figure 3 Front cover CS6K-295MS model

2.2 CHARACTERIZATION TESTS

The samples have been characterized before and after the exposure with the following tests:

- **PERFORMANCE AT STANDARD TEST CONDITIONS (STC)** according to IEC 61215-1-1:2016 standard clause 11.6.
  The test includes the I-V curve measurement of the module at Standard Test Conditions (STC: (25 ± 2) ºC, 1000 W/m^2 with AM1.5G spectral distribution).
  The values presented correspond to the data corrected to STC so all of them are exactly at the same conditions.
- **ELECTROLUMINESCENCE CHARACTERIZATION** according to CENER internal procedure ME.511/36.
  This technique with spatial resolution (pictures) allows identifying cells or defective areas within the module.
  The measurement will be done at dark conditions, applying 2 different biasing conditions to extract the maximum information about the defects detected: (1) Biasing current close to the current at the maximum power point defined by the manufacturer ($I_{APPL1} \approx I_{SC}$) and (2) a biasing current ten times below the current at maximum power point ($I_{APPL2} \approx I_{SC}/10$).

The obtained results are depicted in the following clauses.

2.2.1 PERFORMANCE AT STANDARD TEST CONDITIONS (STC)

Results of performance of samples at Standard Test Conditions (STC) are summarized below.

TEST PARAMETERS					
MODEL	CS6K-295MS	TEMPERATURE COEFFICIENT OF I_{SC}	5.17 mA/ºC	TEMPERATURE COEFFICIENT OF V_{OC}	-118.5 mV/ºC

BEFORE EXPOSURE

TEST RESULTS									
TEST NUMBER	SERIAL NUMBER DATE	T	IRRAD.	P_{MAX}	I_{SC}	V_{OC}	I_{MP}	V_{MP}	FF
30.3734.0-001-MQT06.1FCEM-R001	11810481170589 26/05/2020	25 ºC	1000 W/m^2	292.1W ± 2.2%	9.50A ± 2.0%	39.9V ± 0.4%	8.96A ± 2.1%	32.6V ± 0.8%	77.2% ± 0.6%
30.3734.0-003-MQT06.1FCEM-R001	11810481170711 26/05/2020	25 ºC	1000 W/m^2	292.2W ± 2.2%	9.48A ± 2.0%	39.8V ± 0.4%	8.95A ± 2.1%	32.6V ± 0.8%	77.5% ± 0.6%

Table 1 Performance at STC results (initial)

AFTER EXPOSURE

TEST RESULTS									
TEST NUMBER	SERIAL NUMBER DATE	T	IRRAD.	P_{MAX}	I_{SC}	V_{OC}	I_{MP}	V_{MP}	FF
30.3734.0-001-MQT06.1FCEM-R002	11810481170589 02/06/2020	25 ºC	1000 W/m^2	292.5W ± 2.2%	9.51A ± 2.0%	39.8V ± 0.4%	8.97A ± 2.1%	32.6V ± 0.8%	77.2% ± 0.6%
30.3734.0-003-MQT06.1FCEM-R002	11810481170711 02/06/2020	25 ºC	1000 W/m^2	291.7W ± 2.2%	9.45A ± 2.0%	39.8V ± 0.4%	8.93A ± 2.1%	32.7V ± 0.8%	77.6% ± 0.6%

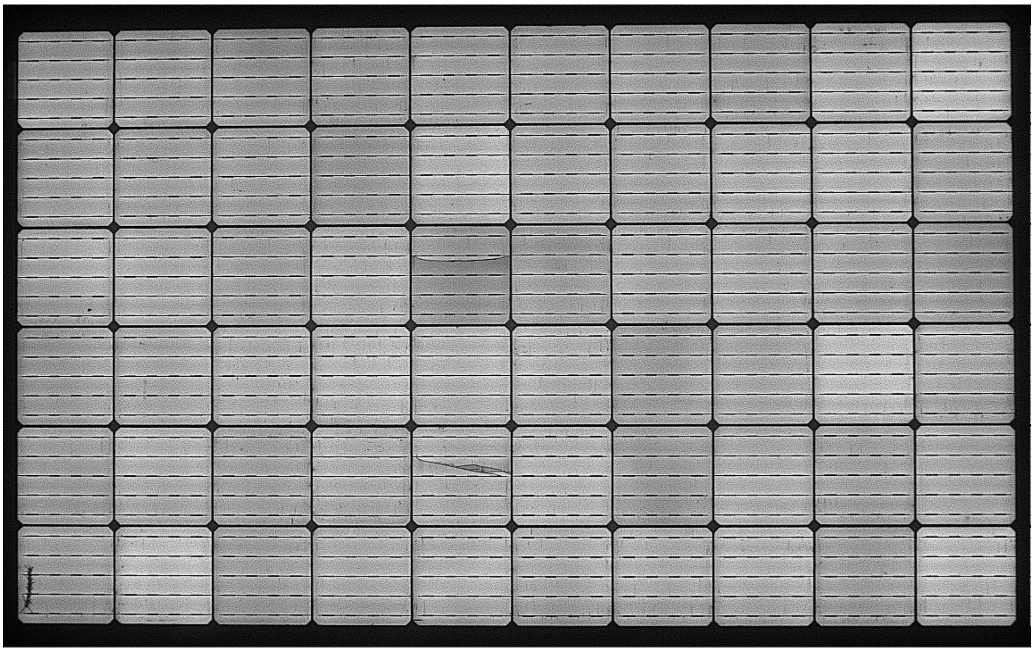
Table 2 Performance at STC results (after exposure)

2.2.2 ELECTROLUMINESCENCE CHARACTERIZATION

BEFORE EXPOSURE

TEST PARAMETERS				
TEST NUMBER	SERIAL NUMBER	DATE	$I_{APPL.1}$	$I_{APPL.2}$
30.3734.0-001-EL.02ELDP-R001	11810481170589	26/05/2020	9.75 A	0.92 A

TEST RESULTS



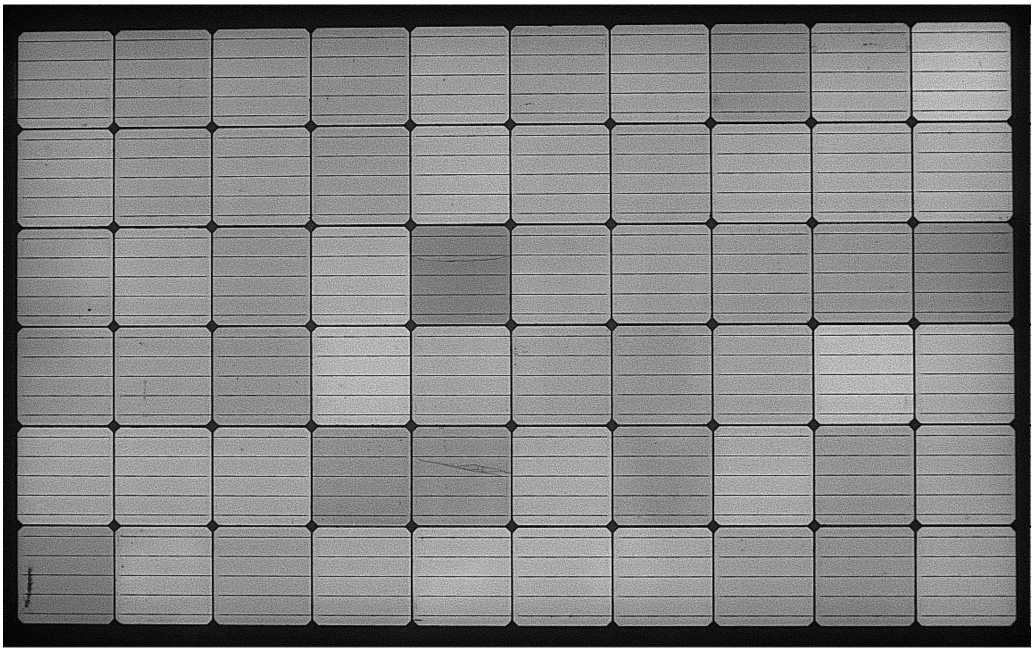
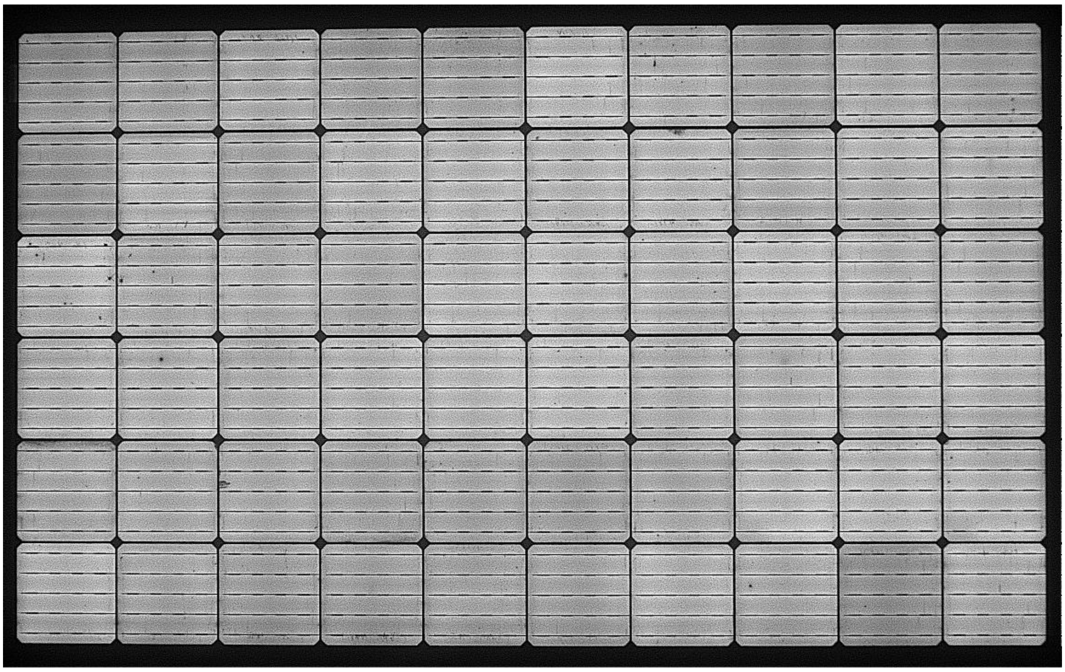


Figure 4 High-biasing and low-biasing electroluminescence of module 30.3734.0-001

TEST PARAMETERS				
TEST NUMBER	SERIAL NUMBER	DATE	$I_{APPL.1}$	$I_{APPL.2}$
30.3734.0-003-EL.02ELDP-R001	11810481170711	26/05/2020	9.75 A	0.92 A

TEST RESULTS



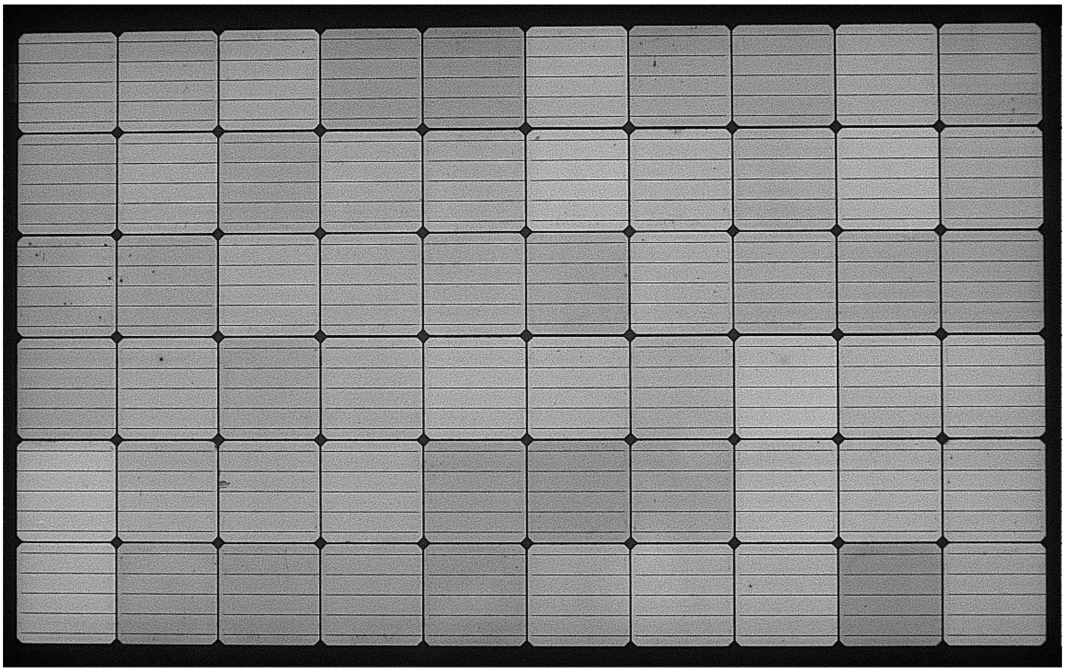
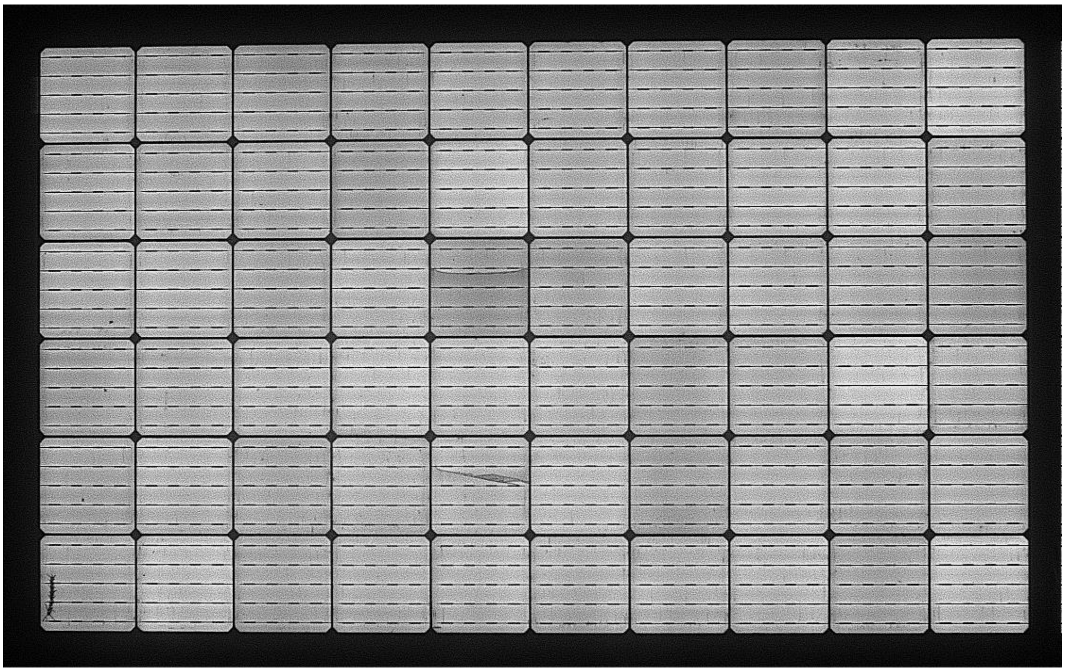


Figure 5 High-biasing and low-biasing electroluminescence of module 30.3734.0-003

AFTER EXPOSURE

TEST PARAMETERS				
TEST NUMBER	SERIAL NUMBER	DATE	$I_{APPL.1}$	$I_{APPL.2}$
30.3734.0-001-EL.02ELDP-R002	11810481170589	06/02/2020	9.75 A	0.92 A

TEST RESULTS



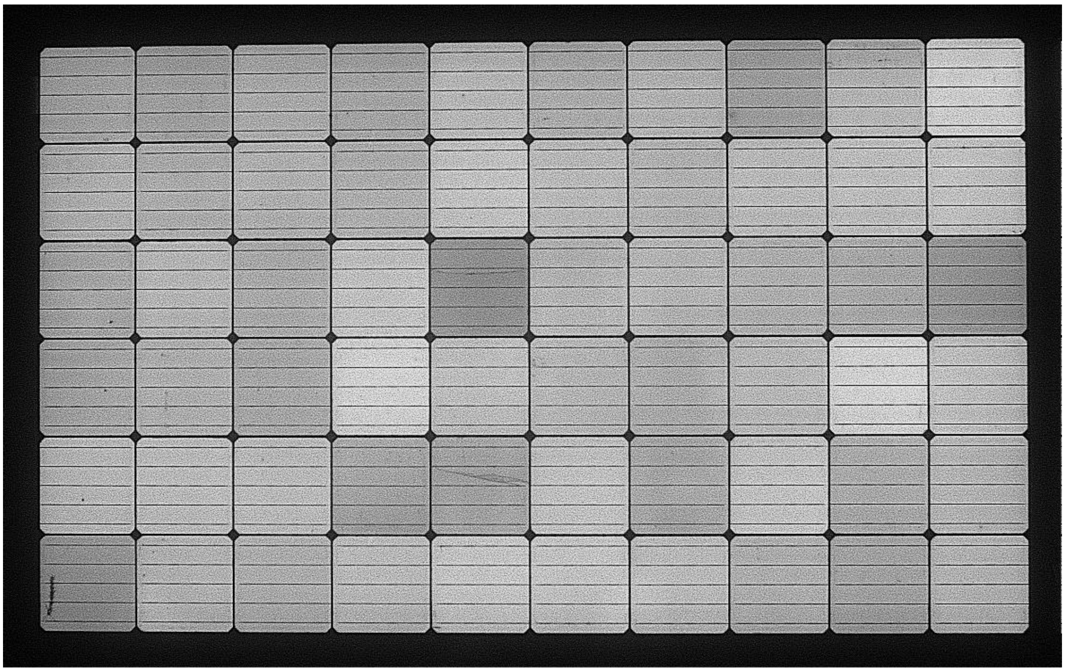
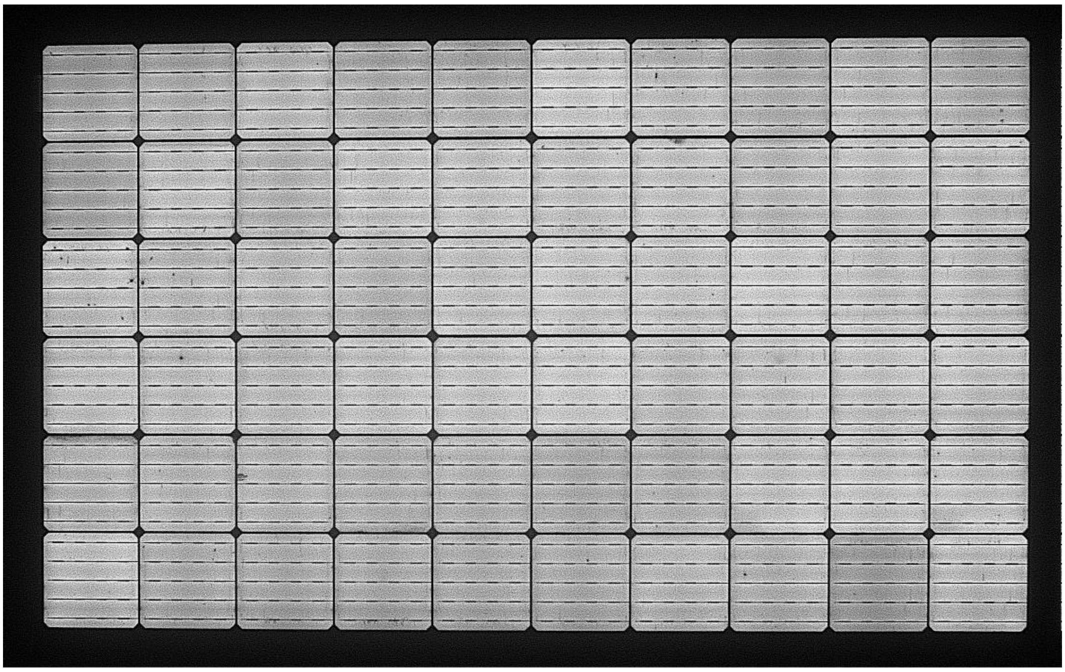


Figure 6 High-biasing and low-biasing electroluminescence of module 30.3734.0-001

TEST PARAMETERS				
TEST NUMBER	SERIAL NUMBER	DATE	$I_{APPL.1}$	$I_{APPL.2}$
30.3734.0-003-EL.02ELDP-R002	11810481170711	06/02/2020	9.75 A	0.92 A

TEST RESULTS



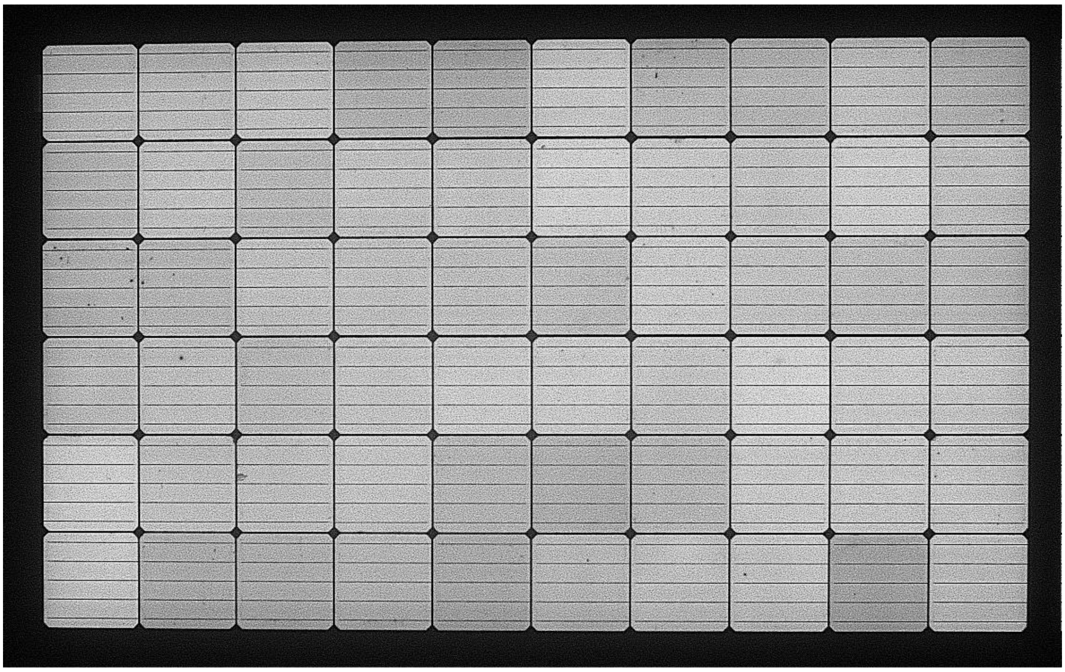


Figure 7 High-biasing and low-biasing electroluminescence of module 30.3734.0-003

2.2.3 TEST RESULTS SUMMARY

PERFORMANCE AT STC TEST

In the initial measurement, the modules show a value of the maximum power (P_{MAX}) below the nominal maximum power value declared in their nameplates (292.1 W and 292.2 W versus 295.0 W).

No changes are observed in the maximum power values after the 2 days exposure. The maximum power values show a variation of +0.1% and -0.2%.

ELECTROLUMINESCENCE CHARACTERIZATION

Minor defects are observed in the initial electroluminescence images.

The PVT sample shows low-importance cracks in 2 cells, and a scratch in other cell. The standard PV module does not practically show defects. Only some stains in the cells or a small crack in a cell.

Although there is no affection in the maximum power of the PVT collector, the presence of these cracks could become a serious problem if their evolution with time and exposure makes them increase. The manufacturing process of the PVT collector has to be very careful because the backsheet and cells of the PV module are very sensitive to mechanical stresses.

After the exposure, no new defects are detected in the EL images of both modules. The defects observed in the initial characterization remain unchanged.

2.3 TEST METHODOLOGY

The methodology for the electrical performance comparison was the measurement the following parameters:

- irradiance over the collection plane (W/m^2),
- devices temperature (ºC),
- voltage (V) and current (A) generated in each sample.

After that, the following calculations were done for PV module and PVT collector:

- irradiation (Wh/m^2),
- electrical power (W),
- energy generated (Wh),
- efficiency (%)
- performance ratio (%)

Finally, comparison of results for both devices was done in numerical tables and graphics.

From the point of view of a photovoltaic device, both modules have been operating at their maximum power point through the connection to a maximum power point tracking system (MPPT). In addition, heat exchanger of the PVT collector has been operated with a water flow across the heat exchanger for the full exposure time.

This comparison was made during spring season (28^{th} and 29^{th} of May) in two complete days (clear days or almost clear days with low wind speed). According to client request, this comparison of generated energy, efficiency and PR was performed at 5º and 35º with fixed tilt for the complete day.

Figure 8 Assembly of solar components at fixed tilt.
Left, PV module. Center, Solar Thermal collector. Right PVT collector.
Testing location: Sarriguren, Spain Latitude 42,8º Longitude -1,6º.

2.4 TEST CONDITIONS

Several parameters were monitored simultaneously for each sample such as solar irradiance, ambient temperature, sample temperature, DC output voltage and DC output current rate for every 2 seconds. Sample temperature was calculated as average of the measures of four temperature probes (k-type thermocouple) placed at the rear side of the device according to IEC 60904-10 in order to obtain a homogenous temperature for the whole device.

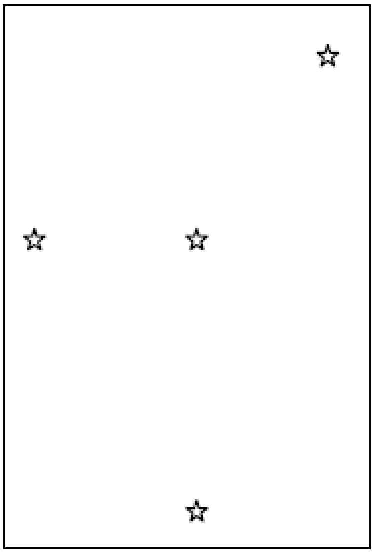


Figure 9 Temperature probes placement at the rear side of the device, according to IEC 60904-10..

Following, maximum, minimum and daily average test conditions reached for each day are shown.

Day 28/05/2020 – Tilt 5°				
Time Period 8:37:31 20:46:45	**Irradiance G (W/m^2)**	**Ambient Air Temperature (°C)**	**PV Module Sample Temperature (°C) (30.3734.0-001)**	**PVT Collector Sample Temperature (°C) (30.3734.0-003)**
Min.	72	17.6	23.1	27.7
Max.	1004	32.1	60.9	47.5

Table 3 Data at tilt angle of 5º (28/05/2020).

Day 29/05/2020 – Tilt 35°				
Time Period 8:27:41 20:20:07	**Irradiance G (W/m^2)**	**Ambient Air Temperature (°C)**	**PV Module Sample Temperature (°C) (30.3734.0-001)**	**PVT Collector Sample Temperature (°C) (30.3734.0-003)**
Min.	79	16.1	16.4	26.4
Max.	1034	30.6	60.1	49.6

Table 4 Data at tilt angle of 35º (29/05/2020).

2.5 RESULTS

In order to make a comparison, device efficiency during the exposure period has been calculated for both samples according to the expression shown below. Sample efficiency indicates the energy conversion ratio of the device between the total solar energy collected versus the total electrical energy generated in a specified period of time.

$$\eta = \frac{H \cdot s}{E}$$

Where:

- η: Device efficiency (%).
- H: Global irradiation on the collector plane during the considered period (Wh/m^2).
- s: Total effective surface of the energy conversion device (m^2).
- E: Electrical energy generated by the device during the considered period (Wh).

From the acquired data for each day, comparative graph and table energy values were analysed in order to compare electrical performance of both devices. In first place, Performance Ratio (PR) was calculated, taking into account the expression of the PR, according to IEC 61724-1 Ed.1. PR shows the difference between the real energy production and the expected energy production in a perfect condition without losses.

$$PR = \frac{E}{\frac{H}{I_{STC}} \cdot P}$$

Where:

- PR: Performance ratio (%).
- E: Electrical energy generated by the device (Wh).
- H: Global irradiation on the collector plane (Wh/m^2).
- I_{STC}: Reference irradiation at STC (Standard Test Conditions), value of 1000 W/m^2.
- P: Peak power of the photovoltaic device (W).

NOTE: Calculations of Global Irradiation (H) and Electrical Energy generated (E) are made by integration of all measurements of irradiance an electric power registered each 2 seconds.

In the next clauses, results and a comparative analysis between PVT collector and PV module are presented. In the full day data analysis, a shading effect over the PVT collector at the last hours of the day was detected. For this reason, it was necessary to carry out a new analysis considering only the period of time free of shading effects on both PV modules (stand alone and PVT). Both analyses are presented below.

2.5.1 FULL DAY DATA ANALYSYS

Tilt 5° – Day 28/05/2020 Time Period: 8:37 to 20:46					
Sample	Solar irradiation H (Wh/m^2)	Energy production E (Wh)	Performance Ratio PR (%)	Average Sample Temperature (°C)	Sample Efficiency η(%)
30.3734.0-01 FEGEN PVT CSK6-16PS.	8262	2109	87.3%	40.3	15.6%
30.3734.0-03 CANADIAN SOLAR CS6K-295MS	8262	2113	87.5.%	46.9	15.6%

Table 5 Results at tilt angle of 5º (28/05/2020).

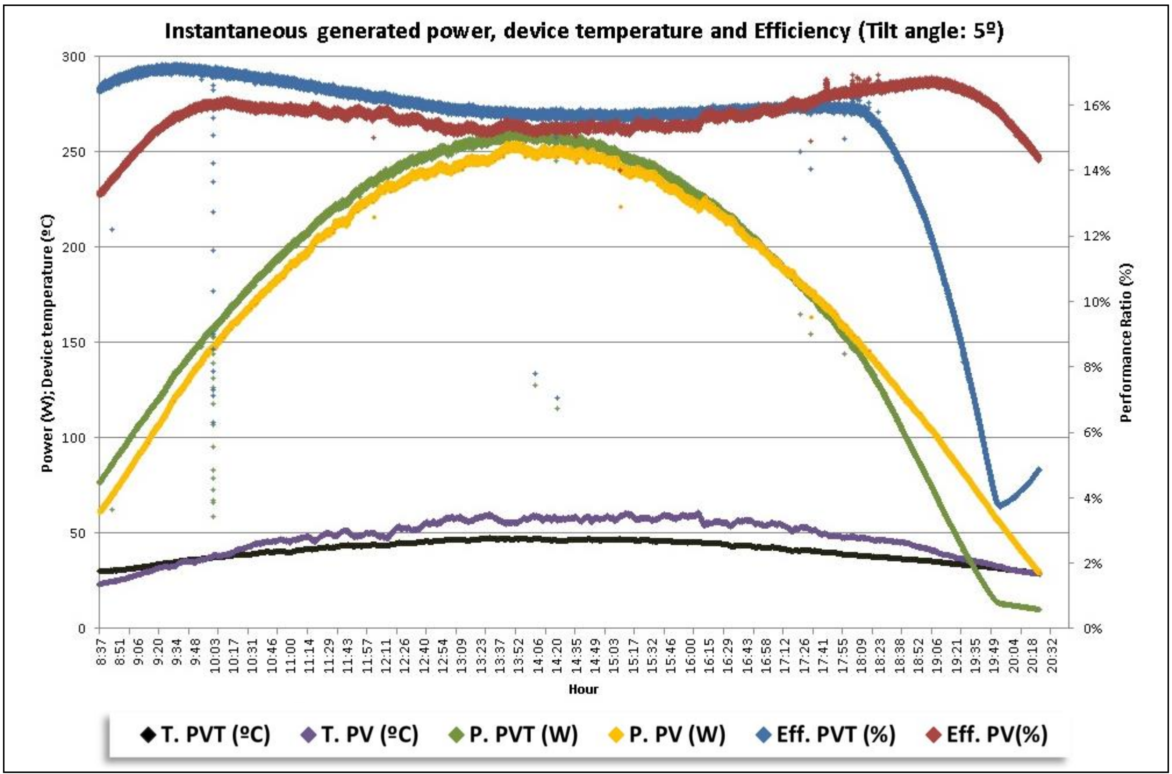


Figure 10 Comparative graph of electrical performance at tilt angle of 5º (28/05/2020).

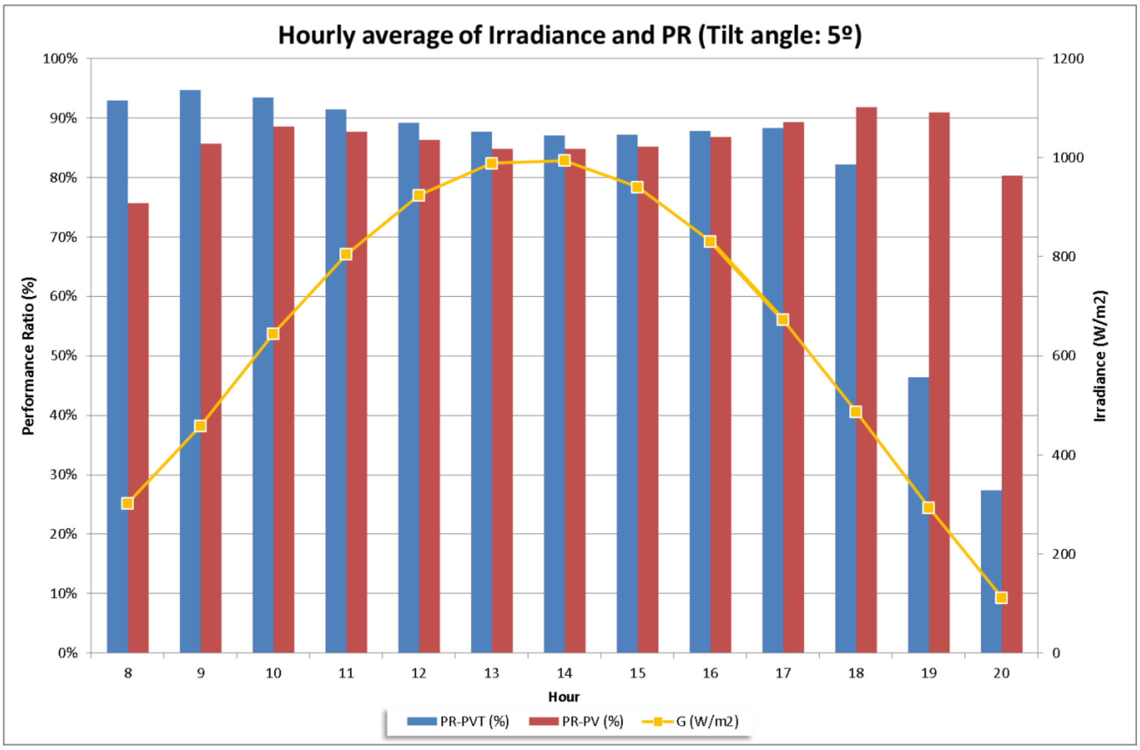


Figure 11 Comparative graph of PR at tilt angle of 5º (28/05/2020).

Tilt 35° – Day 29/05/2020 Time Period 8:22 to 20:20					
Sample	**Solar irradiation H (Wh/m²)**	**Energy production E (Wh)**	**Performance Ratio PR (%)**	**Device Temperature (°C)**	**Device Efficiency η(%)**
30.3734.0-01 FEGEN PVT CSK6-16PS.	7927	2009	86.7%	40.1	15.5%
30.3734.0-03 CANADIAN SOLAR CS6K-295MS	7927	2016	87.0%	42.1	15.5%

Table 6 Results at tilt angle of 35º (28/05/2020).

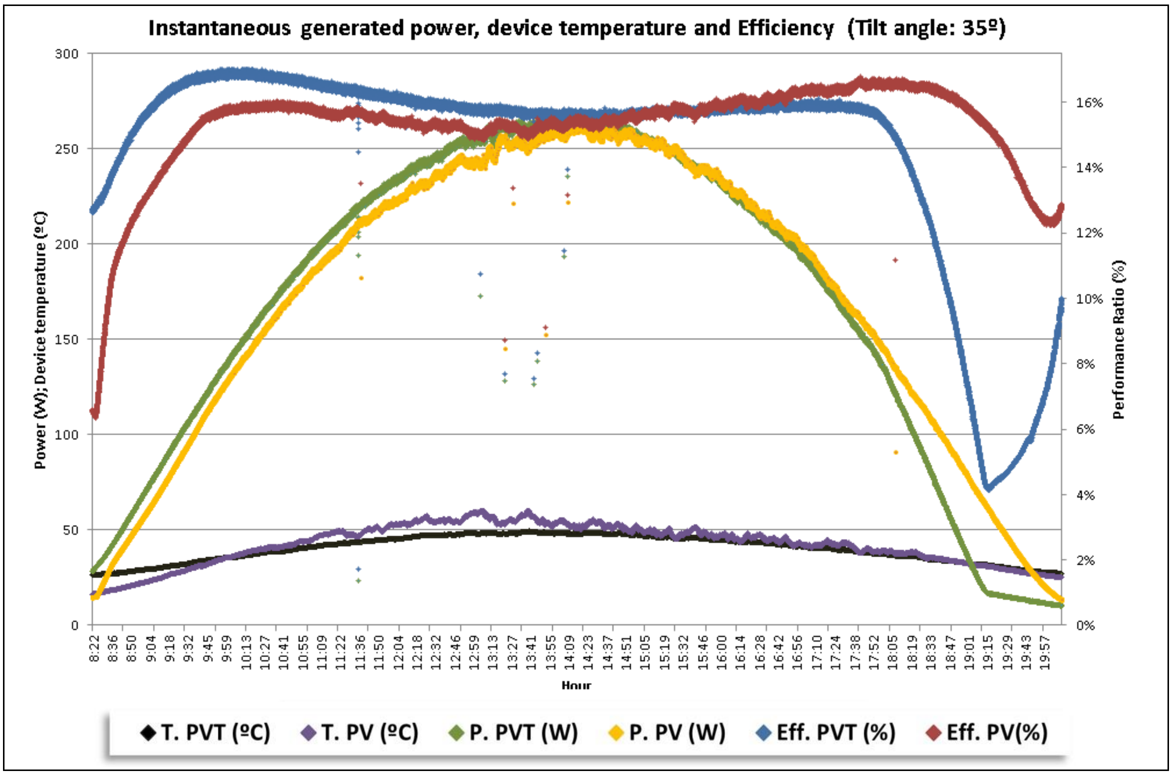


Figure 12 Comparative graph of electrical performance at tilt angle of 35º (29/05/2020).

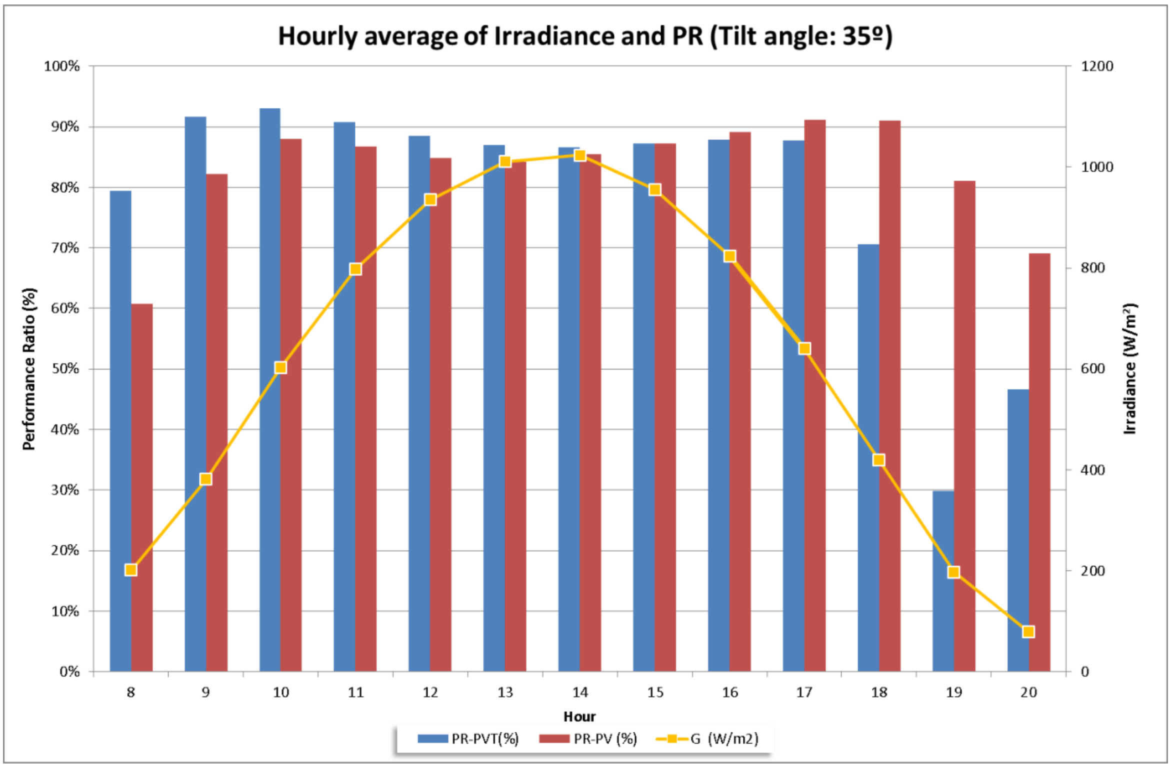


Figure 13 Comparative graph of PR at tilt angle of 35º (29/05/2020).

The main conclusions shown in this study are following exposed:

- The efficiency and performance ratio obtained by both devices at 5º and 35º tilt are practically identical, very similar. Both devices presented a better PR at tilt angle of 5º.
- Maximum and average temperature of PVT collector is always lower than stand-alone PV device in all cases.
- Results summarized above must be considered very carefully, due to the presence of a shading effect over the PVT collector at the last hours of the day. For this reason, a new analysis is presented considering a period of time free of shadings effects. Time period and figures are presented below.

Sample	Tilt: 35º		Tilt: 5º	
	Performance Ratio PR (%)	Device Efficiency η(%)	Performance Ratio PR (%)	Device Efficiency η(%)
30.3734.0-01 FEGEN PVT CSK6-16PS.	86.7%	15.5%	87.3%	15.6%
30.3734.0-03 CANADIAN SOLAR CS6K-295MS	87.0%	15.5%	87.5%	15.6%

Table 7 Summary results of PR and Efficiency for a full day

2.5.3 PARTIAL DAY DATA ANALYSYS (WITHOUT SHADOWS)

According to a ray-tracing analysis performed by CENER, shading effects were identified in different moments of the day depending on the tilt angle.

- For a tilt angle of 5º, time period with no shadings effects is from 8:37h to 17:15h.
- For a tilt angle of 35º, time period with no shadings effects is from 8:22h to 16:45h.

Based on results exposed above, partial day analysis is presented following:

Tilt 5° – Day 28/05/2020 Time Period: 8:37 to 17:15					
Sample	Solar irradiation H (Wh/m^2)	Energy production E (Wh)	Performance Ratio PR (%)	Average Sample Temperature (°C)	Sample Efficiency η(%)
30.3734.0-03 FEGEN PVT CSK6-16PS.	6891	1815	90.1%	42.4	16.1%
30.3734.0-01 CANADIAN SOLAR CS6K-295MS	6891	1748	86.8%	49.6	15.5%

Table 8 Results at tilt angle of 5º (28/05/2020, Time Period 8:37- 17:15).

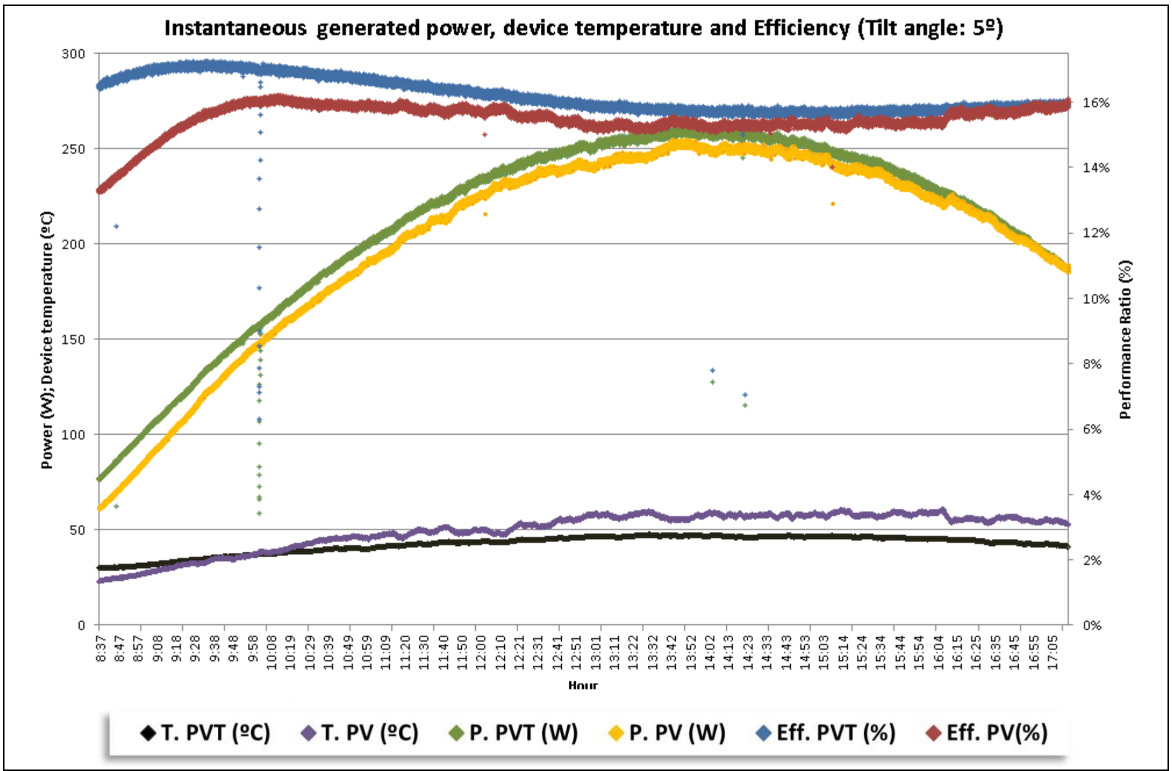


Figure 14 Comparative graph of electrical performance at tilt angle of 5º (28/05/2020, Time Period 8:37- 17:15).

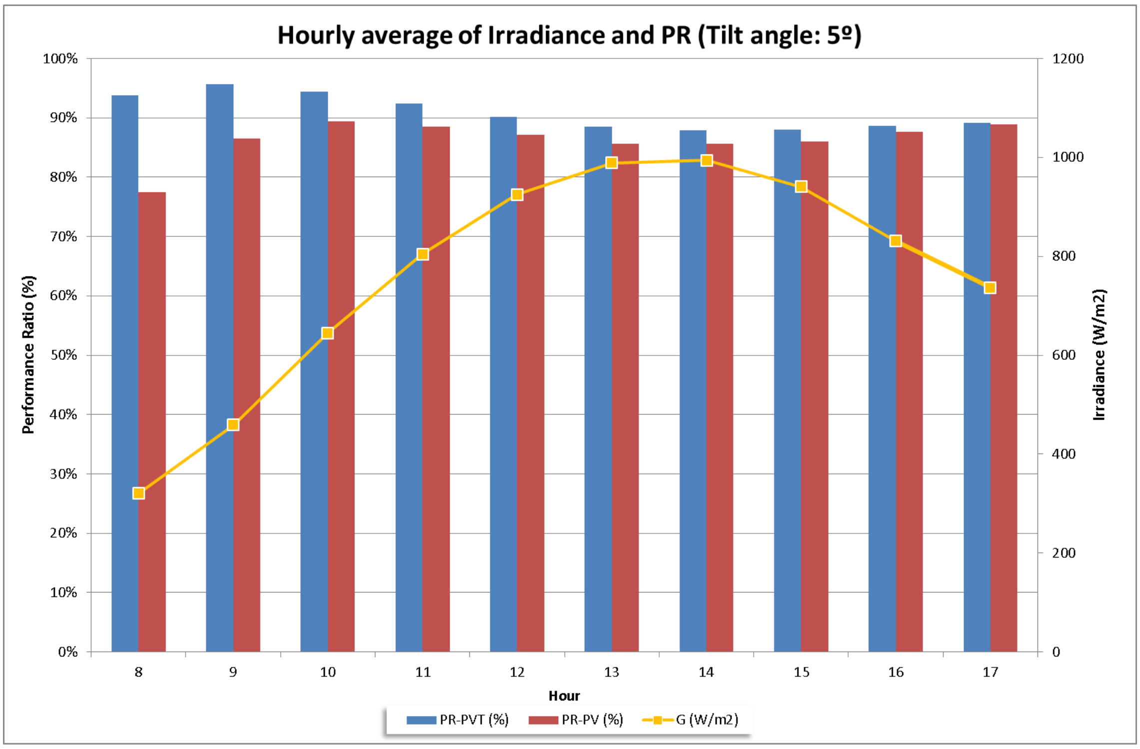


Figure 15 Comparative graph of PR at tilt angle of 5º (28/05/2020, Time Period 8:37 - 17:15).

Tilt 35° – Day 29/05/2020 Time Period 8:22 to 16:45					
Sample	Solar irradiation H (Wh/m^2)	Energy production E (Wh)	Performance Ratio PR (%)	Average Device Temperature (°C)	Device Efficiency η(%)
30.3734.0-03 FEGEN PVT CSK6-16PS.	6465	1686	89.3%	42.1	15.9%
30.3734.0-01 CANADIAN SOLAR CS6K-295MS	6465	1631	86.3%	44.8	15.4%

Table 9 Results at tilt angle of 35º (29/05/2020, Time Period 8:22 - 16:45).

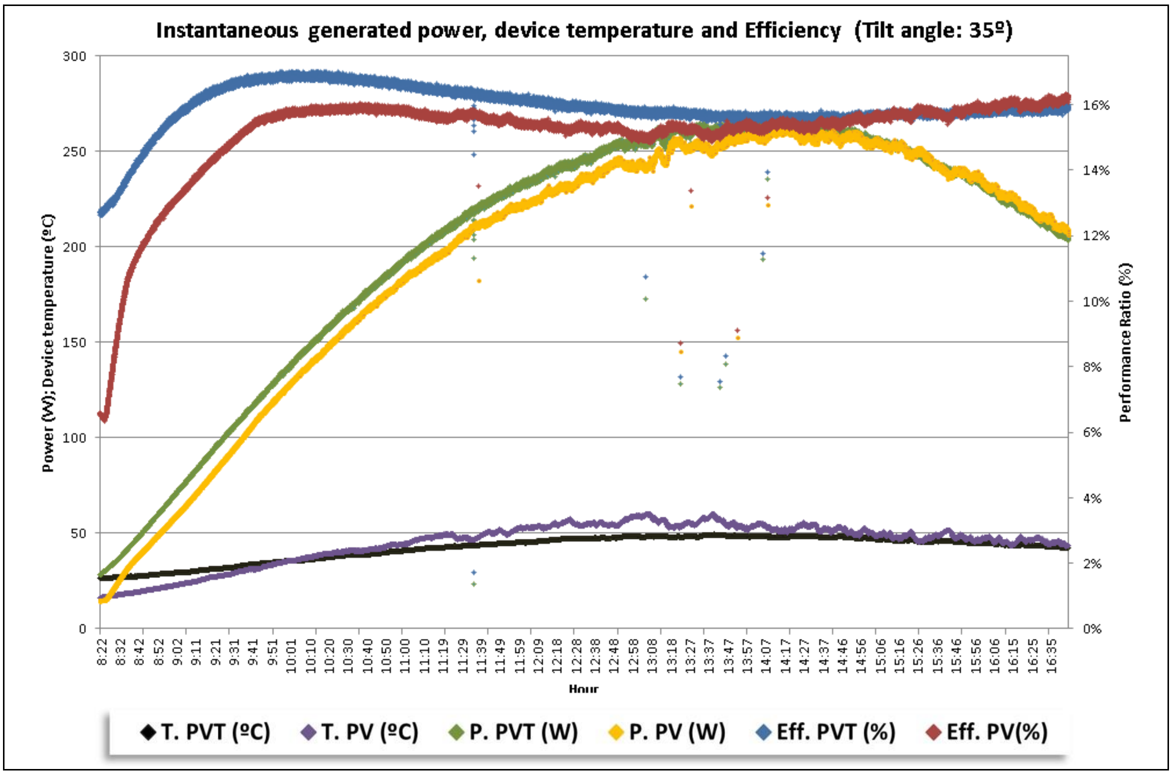


Figure 16 Comparative graph of electrical performance at tilt angle of 35º (29/05/2020, Time Period 8:22- 16:45).

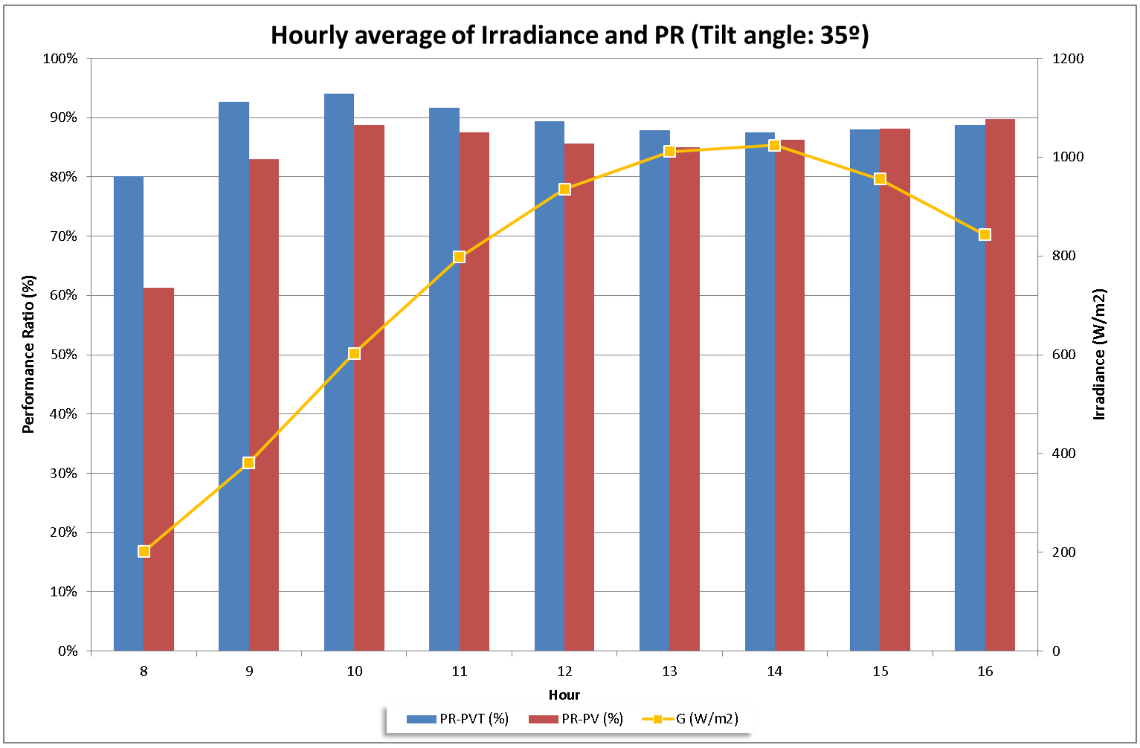


Figure 17 Comparative graph of PR at tilt angle of 35º (29/05/2020, Time Period 8:22 - 16:45).

After this new analysis, main conclusions are following exposed:

- Behavior of the PVT collector is better than stand-alone PV module in average values of energy generated, Efficiency and PR in all cases for 5º and 35º of tilt angle. This result is consistent with the fact that the module onto the PVT collector has a lower operating temperature than stand-alone PV module, which results in lower temperature losses and therefore a better PR.
- For the considered time period of testing, tilt angle of 5º presents a higher value of irradiation and generated energy than 35º. These results will probably change in different time of periods along the year. The same measurements will be performed three more times (in summer, in autumn and in winter) in order to identify the existence of those differences.

Sample	Tilt: 35º		Tilt: 5º	
	Performance Ratio PR (%)	Device Efficiency η (%)	Performance Ratio PR (%)	Device Efficiency η (%)
30.3734.0-01 FEGEN PVT CSK6-16PS.	89.3%	15.9%	90.1%	16.1%
30.3734.0-03 CANADIAN SOLAR CS6K-295MS	86.3%	15.4%	86.8%	15.5%

Table 10 Summary results of PR and Efficiency for a partial day (without shadows)

These conclusions can only be applied for the samples tested, location and meteorological conditions at the time of the test.