CENER | CENTRO NACIONAL DE ENERGÍAS RENOVABLES FUNDACIÓN CENER | NATIONAL RENEWABLE ENERGY CENTRE

ADItech CORPORACIÓN TECNOLÓGICA

Report: 30.3734.0-04-EN

COMPARATIVE PHOTOVOLTAIC PERFORMANCE TESTS PVT COLLECTOR vs. PV MODULE

PHOTOVOLTAIC SOLAR ENERGY DEPARTMENT

NATIONAL ENERGY RENEWABLE CENTRE (CENER)

PAMPLONA
Ciudad de la Innovación 7
31621 Sarriguren
(Navarra) España
T +34 948 25 28 00

SANGÜESA
Polígono Industrial
Rocaforte G2-H1
31400 Sangüesa
(Navarra) España
T + 34 948 87 17 45

AOIZ
Urbanización Área de
Reparto Ar-3,
31430 Aoiz (Navarra)
España
T + 34 948 80 24 12

SEVILLA
Pabellón de Italia
C Isaac Newton nº 4
Módulos A y B
41092 (Sevilla) España
T +34 902 25 28 00

www.cener.com

Title:	COMPARATIVE TESTS PVT COLLECTOR vs. PV MODULE
Code:	30.3734.0-04-EN
Report Emission Office:	Pamplona

Customer:	FEGEN SOLAR LLC.
Contact:	Christos Nikolaidis
Address:	31, Pentelis Av. 15235 Vrilissia, Athens (GREECE)

Written by:	Ildefonso Muñoz	Technician
	Juan Manuel Cuadra	Technician
Checked by:	Jaime Moracho	PV systems Head of Service
Approved by:	Dra. Ana Rosa Lagunas	PV Department Director

Firmado digitalmente por Ana Rosa Lagunas Alonso
Fecha: 2021.04.27 20:28:06 +02'00'

INDEX PAGE

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 during their outside exposure for a full day at the end of March. This test has been done at two different tilts (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 PV module and the PVT have been electrically characterized including Electroluminescence technique before and after the exposure.

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

1.3 CONCLUSIONS

Following, summary results of PR and Efficiency for both tilts are presented in next table.

Sample	Tilt: 5º Date: 24/03/2021 Measurement Period: 10.25 h		Tilt: 35º Date: 23/03/2021 Measurement Period: 10.75 h	
	Performance Ratio PR (%)	Device Efficiency η (%)	Performance Ratio PR (%)	Device Efficiency η (%)
30.3734.0-001 FEGEN PVT CSK6-16PS	94.4%	16.9%	94.4%	16.9%
30.3734.0-003 CANADIAN SOLAR CS6K-295MS	91.8%	16.4%	91.8%	16.4%

Table A Summary results of PR and Efficiency for a full day.

- Related to the location where these tests are performed, for the two tilts used (5º and 35º) higher values of irradiation and energy production were reached at tilt of 35º for both devices (PV and PVT) in the considered measurement time period on each device, as could be expected.
- From a general point of view and considering the specific test conditions for both cases under study (tilt of 5º and 35º), daily values of energy production, PR and efficiency are better in the PVT device. Improvement of PVT device versus PV device in energy production is in the range of 25 Wh/day to 34 Wh/day, improvement of PR is in the range of 1.5% to 3% and improvement of efficiency is in the range of 0.3% to 0.5%.
- In the same way, the behavior and effect of the temperature in the energy production are consistent with expected values for both devices. Comparing them, in the moments of higher differences of temperatures, higher differences of energy, PR and efficiency are obtained; around 5% in PR and 0.8% in efficiency. For all the test conditions performed in the measurement period, the energy production, PR and efficiency values were always better in the PVT device compared to the PV device.

After the exposure, the PV module and the PVT are characterized with the Performance at STC test and Electroluminescence:

- No changes are observed in the electrical parameters of the PV module and the PVT. The maximum power values show a variation of -0.1% and 0.0% in each sample, taking into account that the estimated uncertainty of the measurement of the maximum power is around 2.3%.
- The defects observed in the previous characterization remain unchanged. One new defect is observed in each module (a scratch in module 30.3734.0-001 and a small crack in module 30.3734.0-003). None of the new defects might affect the electrical performance of the modules.

2 TECHNICAL REPORT

2.1 SAMPLES DESCRIPTION

REFERENCE DATA			
Number of samples		2	
Reception date of samples		25/05/2020	
Test period		28/10/2020 – 04/01/2021	
TESTED SAMPLES DESCRIPTION			
INTERNAL CODE	MANUFACTURER	MODEL	SERIAL NUMBER
30.3734.0-001	CANADIAN SOLAR & FEGEN	CS6K-295MS (PV MODULE)	11810481170589
		P-FHE16PS (THERMAL COLLECTOR)	100122190621
30.3734.0-003	CANADIAN SOLAR	CS6K-295MS	11810481170711

ELECTRICAL CHARACTERISTICS		
MODEL	CS6K-295MS 30.3734.0-001	CS6K-295MS 30.3734.0-003
TYPE OF MODEL	PVT collector	Standard PV module
Maximum power (P_{MP}) ..... :	295 W	
Short-circuit current (I_{SC}) ..... :	9.75 A	
Open-circuit voltage (V_{OC}) ..... :	39.5V	
Current at maximum power (I_{MP}) ..... :	9.14 A	
Voltage at maximum power (V_{MP}) ..... :	32.3 V	
Maximum voltage system ..... :	1000 V	
Short-circuit current temperature coefficient (α)[1] ..... :	5.17 mA/ºC	
Open-circuit voltage temperature coefficient (β)[1] ..... :	-118.5 mV/ºC	
Maximum power temperature coefficient (γ) ..... :	-1150 mW/ºC	
Maximum over-current protection rating ..... :	15 A	

[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.

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	

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

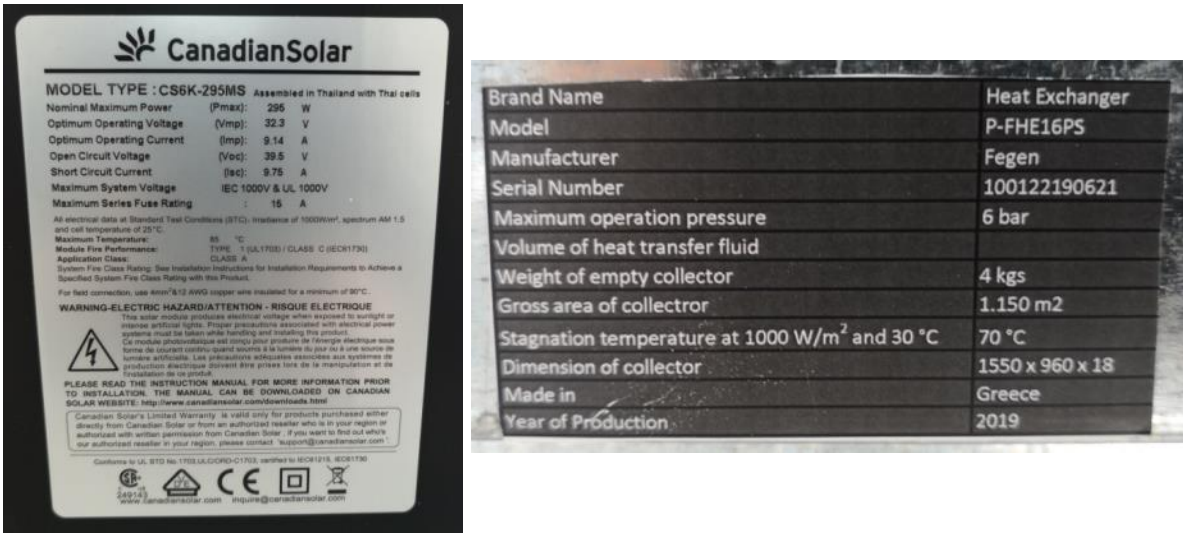

Figure 1 Marking of CS6K-295MS model (standard module) and PVT collector

Figure 2 Front cover of 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-R005 FEGEN PVT - CSK6-16PS	11810481170589 04/01/2021	25 ºC	1000 W/m^2	292.6W ± 2.3%	9.54A ± 2.1%	39.8V ± 0.4%	9.01A ± 2.3%	32.5V ± 0.8%	77.1% ± 0.6%
30.3734.0-003-MQT06.1FCEM-R005 CANADIAN SOLAR - CS6K-295MS	11810481170711 04/01/2021	25 ºC	1000 W/m^2	291.1W ± 2.3%	9.46A ± 2.1%	39.7V ± 0.4%	8.96A ± 2.3%	32.5V ± 0.8%	77.5% ± 0.6%

Table 2 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-R006 FEGEN PVT - CSK6-16PS	11810481170589 14/04/2021	25 ºC	1000 W/m^2	292.3W ± 2.3%	9.53A ± 2.1%	39.8V ± 0.4%	9.00A ± 2.3%	32.5V ± 0.8%	77.1% ± 0.6%
30.3734.0-003-MQT06.1FCEM-R005 CANADIAN SOLAR - CS6K-295MS	11810481170711 14/04/2021	25 ºC	1000 W/m^2	291.0W ± 2.3%	9.49A ± 2.1%	39.6V ± 0.4%	8.97A ± 2.3%	32.4V ± 0.8%	77.4% ± 0.6%

Table 3 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-R005	11810481170589	29/12/2020	9.76 A	0.92 A

TEST RESULTS

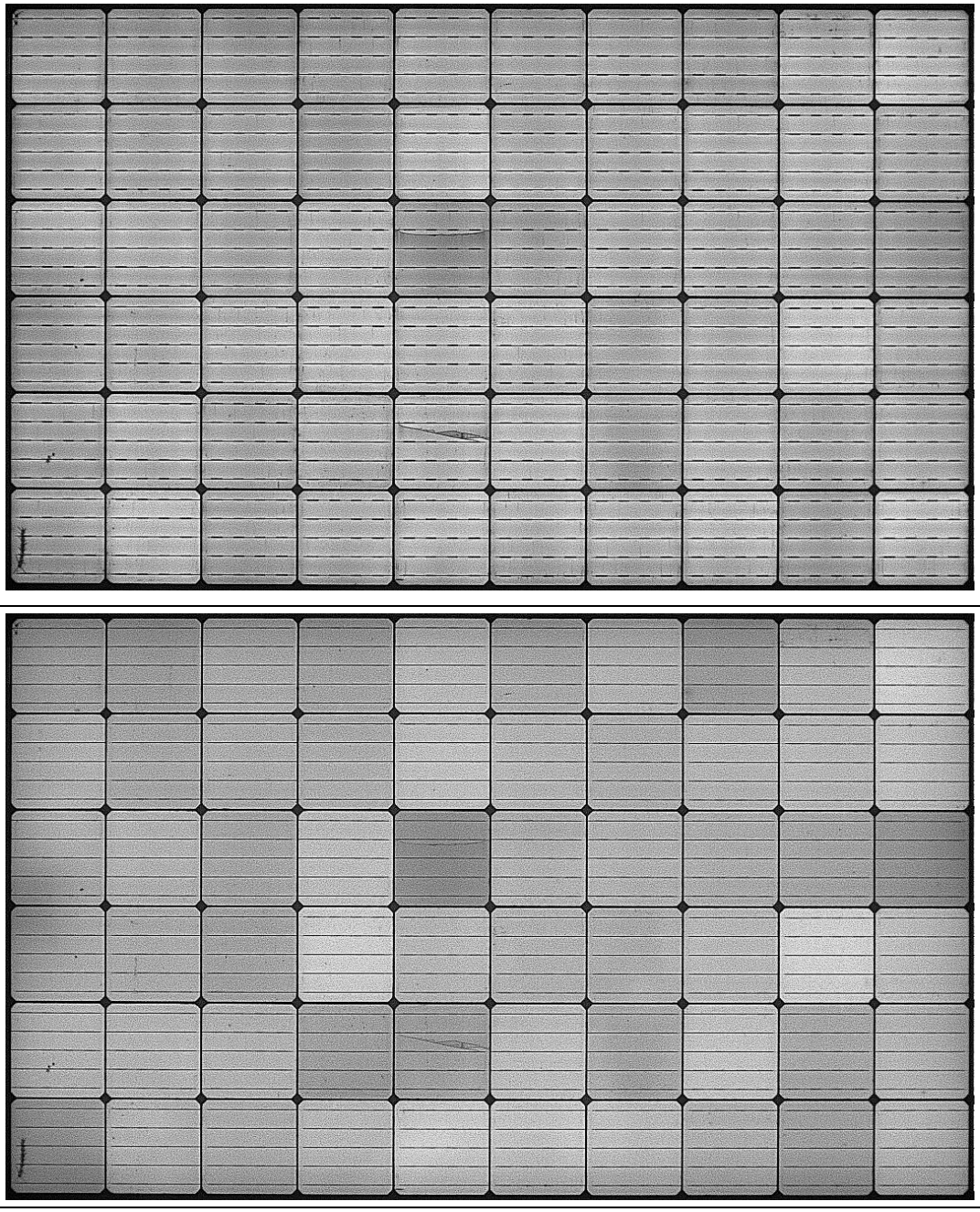

Figure 3 High-biasing and low-biasing electroluminescence of module 30.3734.0-001

TEST PARAMETERS				
TEST NUMBER	SERIAL NUMBER	DATE	$I_{APPL.1}$	$I_{APPL.2}$
30.3734.0-003-EL.02ELDP-R005	11810481170711	29/12/2020	9.76 A	0.92 A
TEST RESULTS				

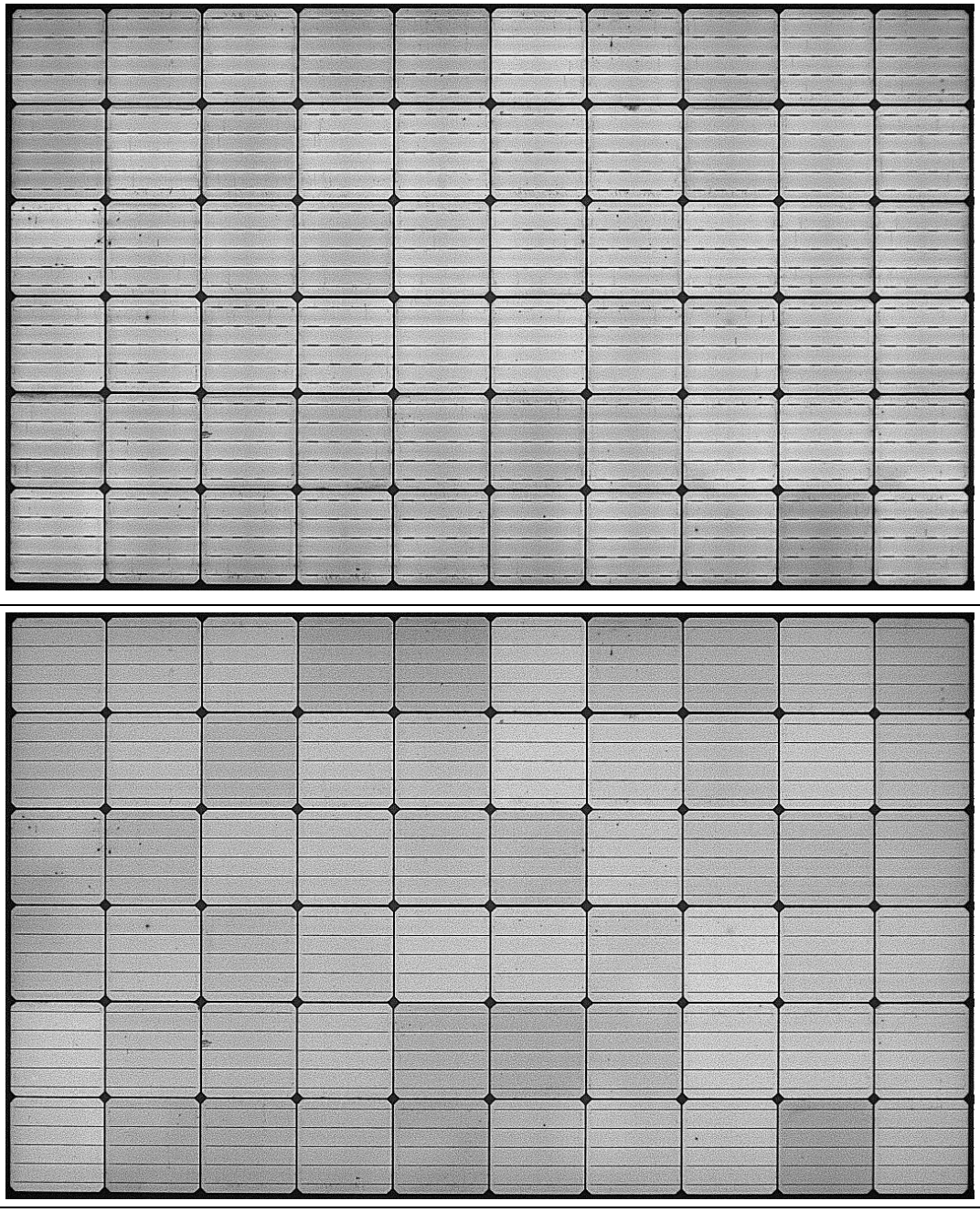

Figure 4 High-biasing and low-biasing electroluminescence of module 30.3734.0-003

AFTER EXPOSURE

TEST PARAMETERS				
TEST NUMBER	SERIAL NUMBER	DATE	$I_{APPL.1}$	$I_{APPL.2}$
30.3734.0-001-EL.02ELDP-R006	11810481170589	14/04/2021	9.64 A	0.86 A

TEST RESULTS

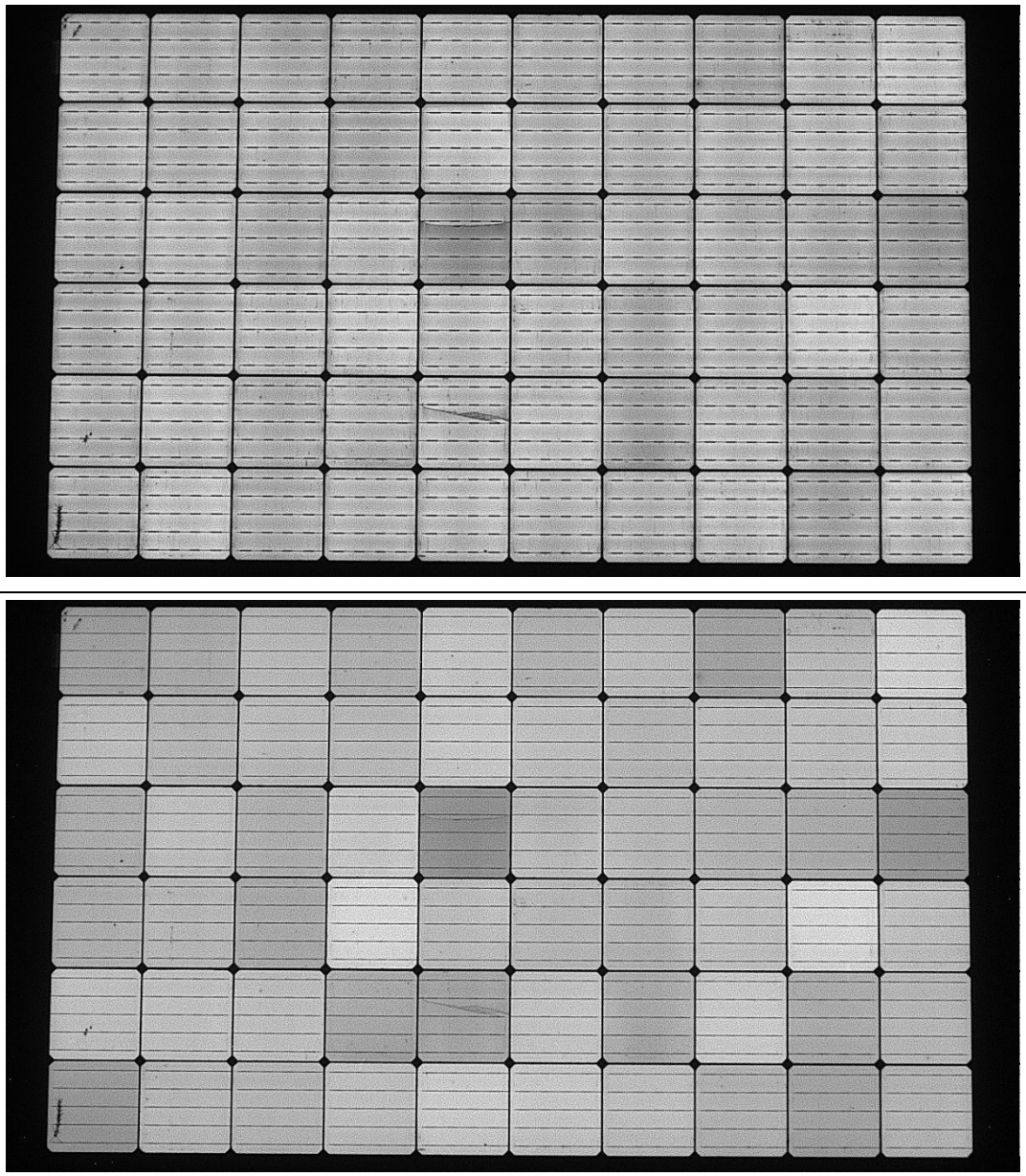

Figure 5 High-biasing and low-biasing electroluminescence of module 30.3734.0-001

TEST PARAMETERS				
TEST NUMBER	SERIAL NUMBER	DATE	$I_{APPL.1}$	$I_{APPL.2}$
30.3734.0-003-EL.02ELDP-R006	11810481170711	14/04/2021	9.65 A	0.86 A
TEST RESULTS				

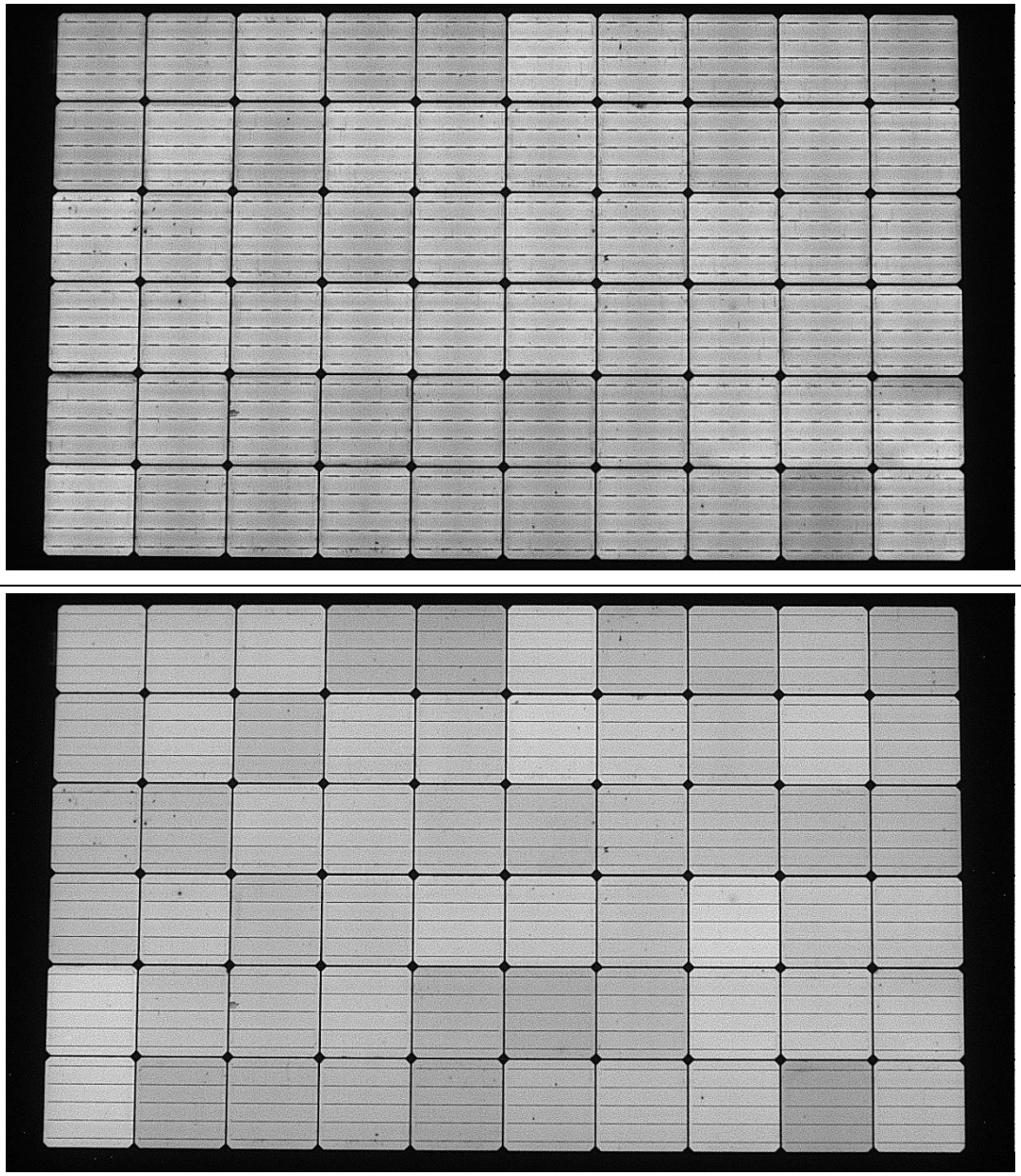

Figure 6 High-biasing and low-biasing electroluminescence of module 30.3734.0-003

2.2.3 TEST RESULTS SUMMARY

PERFORMANCE AT STC TEST

No significant changes are observed in the electrical parameters after the exposure.

The maximum power of module 30.3734.0-001 shows a variation of -0.1% and the maximum power of module 30.3734.0-003 shows a variation of 0.0%.

ELECTROLUMINESCENCE CHARACTERIZATION

The defects observed in the previous characterization remain unchanged.

After the exposure, two small defects are observed in the EL images:

- Module 30.3734.0-001 shows a small scratch in the top-left (F1) cell;
- Module 30.3734.0-003 shows a small crack in cell D7.

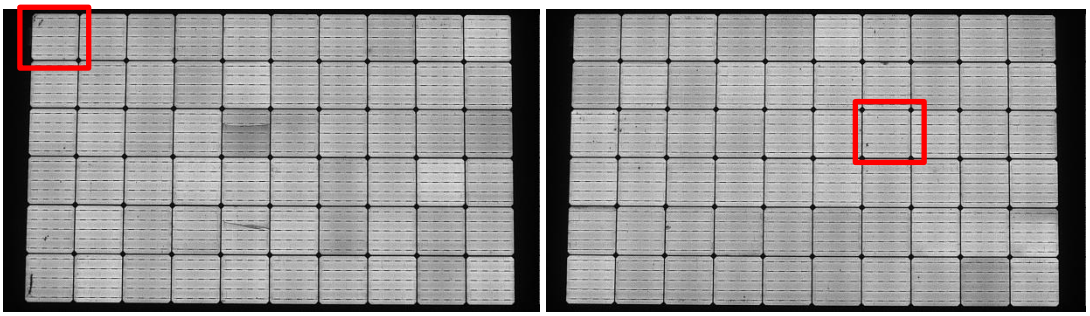

Figura 1 Cell F1 of module 30.3734.0-001 and cell D7 of module 30.3734.0-003

None of the new defects observed in the EL images might affect the electrical performance of the modules.

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.

Figure 7 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.

This comparison is considered for winter season, although the measurement days were in the first days of spring season (23th and 24th of March) due to the fact of did not have adequate

measurement conditions in two complete days (clear days or almost clear days with low wind speed) until these dates. According to the client request, this comparison of generated energy, efficiency and PR was performed at 5º and 35º of fixed tilt for the complete day.

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 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 representative average temperature for the whole device.

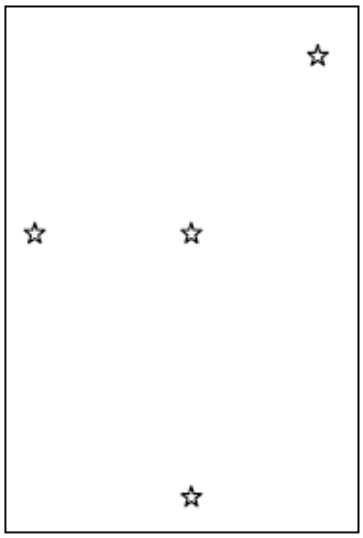

Figure 8 Temperature probes placement at the rear side of the device, according to IEC 60904-10.

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

Day 24/03/2021 – Tilt 5°				
Time Period 8:06:45 18:20:35	**Global Irradiance I_G (W/m^2)**	**Ambient Air Temperature (°C)**	**PV Module Device Temperature (°C) (30.3734.0-003)**	**PVT Collector Device Temperature (°C) (30.3734.0-001)**
Min.	107.8	3.1	3.5	13.2
Max.	876.6	20.8	46.5	32.6
Average	602.2	15.4	33.2	26.3

Table 4 Data at tilt of 5º (24/03/2021).

Day 23/03/2021 – Tilt 35°				
Time Period 7:48:35 18:29:33	**Global Irradiance I_G (W/m^2)**	**Ambient Air Temperature (ºC)**	**PV Module Device Temperature (ºC) (30.3734.0-003)**	**PVT Collector Device Temperature (ºC) (30.3734.0-001)**
Min.	45.2	4.5	0.9	10.6
Max.	1085.2	19.3	51.7	36.8
Average	706.8	14.7	31.4	27.4

Table 5 Data at tilt of 35º (23/03/2021).

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 electrical energy generated versus the total solar energy collected in a specified period of time.

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

Where:

- η: Device efficiency (%).
- H_G: 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.

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

Where:

- PR: Performance ratio (%).
- E: Electrical energy generated by the device (Wh).
- H_G: Global irradiation on the collector plane (Wh/m^2).
- I_{STC}: Reference irradiance 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_G) and Electrical Energy generated (E) are made by integration of all measurements of irradiance an electric power registered each 2 seconds.

Tilt 5° – Day 24/03/2021; Time Period: 8:06:45 – 18:20:35					
Sample	**Global Solar irradiation H_G (Wh/m^2)**	**Energy production E (Wh)**	**Performance Ratio PR (%)**	**Average Device Temperature (°C)**	**Device Efficiency η (%)**
30.3734.0-001 FEGEN PVT CSK6-16PS	6161	761	94.4	26.3	16.9
30.3734.0-003 CANADIAN SOLAR CS6K-295MS	6161	736	91.8	33.2	16.4

Table 6 Results at tilt of 5º (24/03/2021).

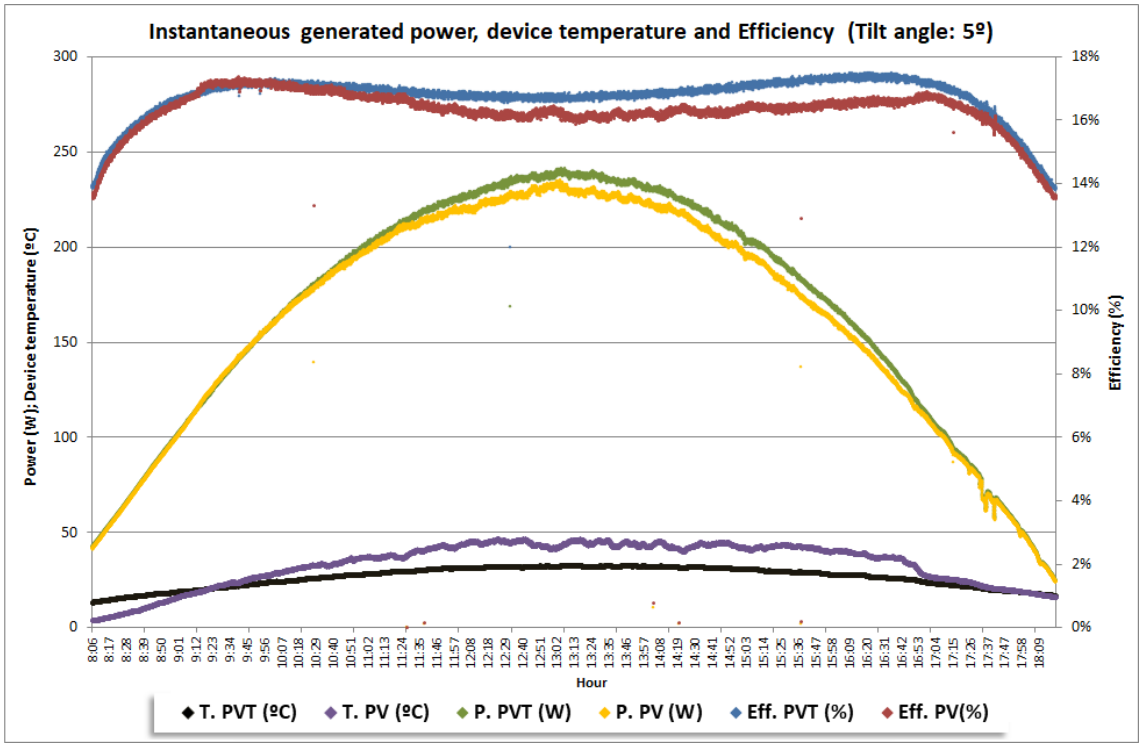

Figure 9 Comparative graph of electrical performance at tilt of 5º (24/03/2021).

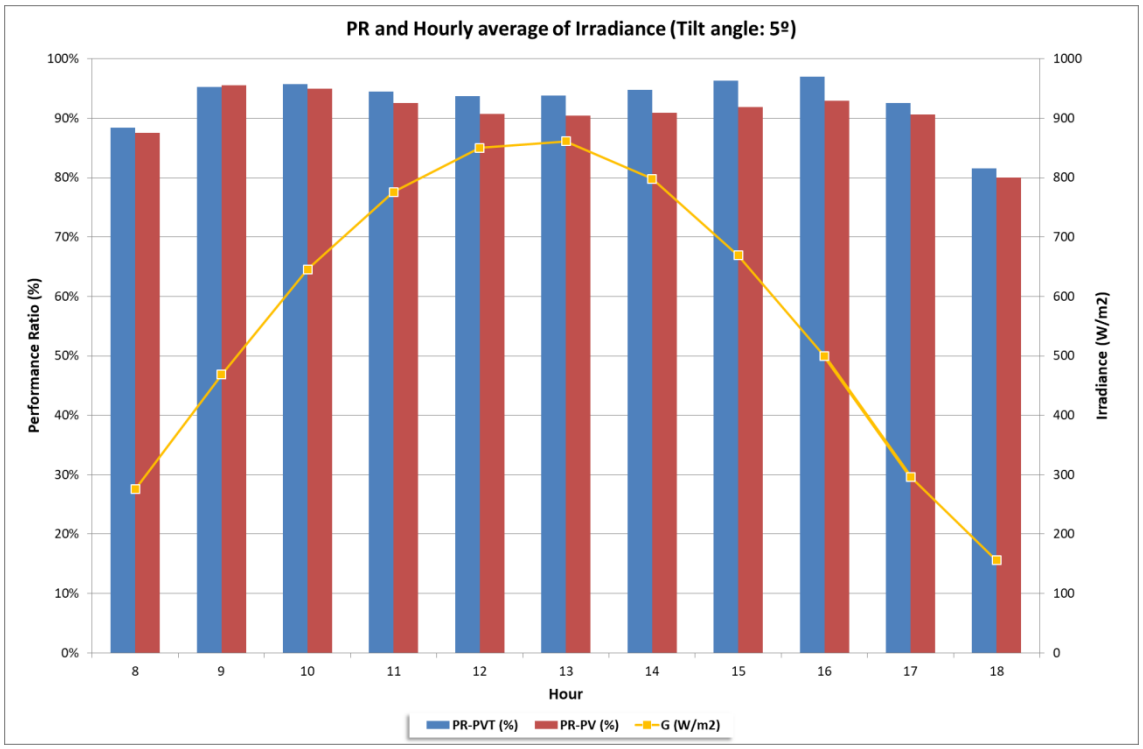

Figure 10 Comparative graph of PR at tilt of 5º (24/03/2021).

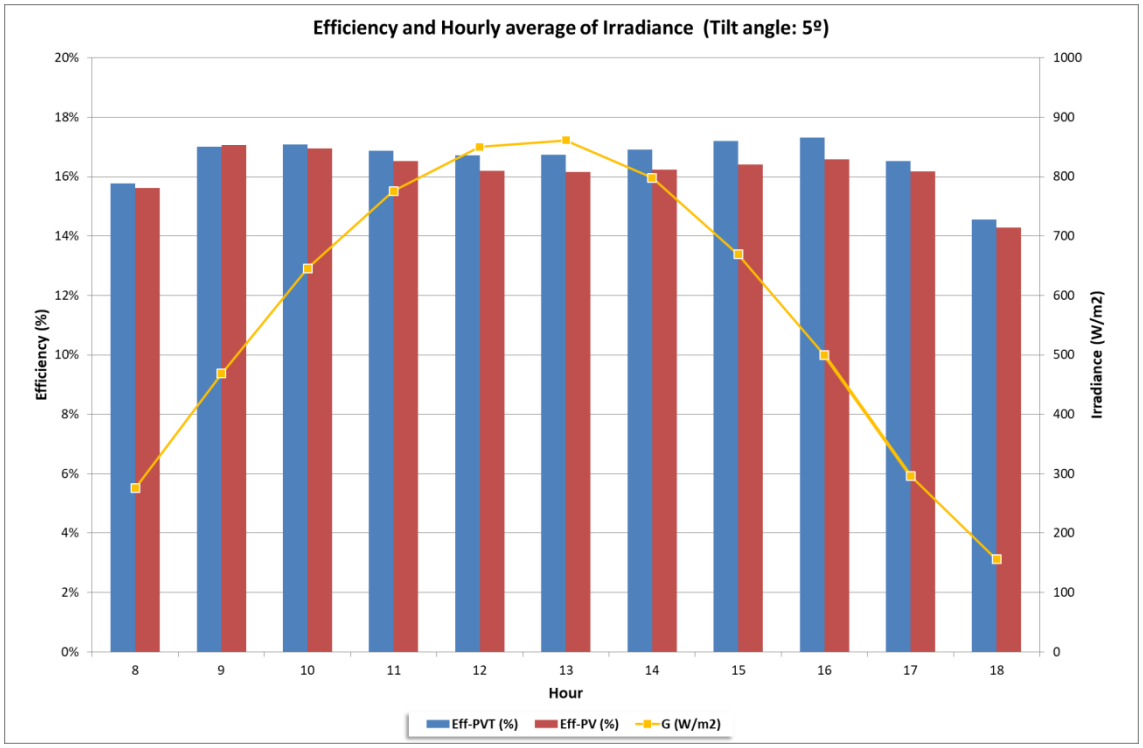

Figure 11 Comparative graph of Efficiency at tilt of 5º (24/03/2021).

Tilt 35° – Day 23/03/2021; Time Period: 7:48:35 – 18:29:33					
Sample	**Global Solar irradiation H_G (Wh/m^2)**	**Energy production E (Wh)**	**Performance Ratio PR (%)**	**Average Device Temperature (°C)**	**Device Efficiency η (%)**
30.3734.0-001 FEGEN PVT CSK6-16PS	7845	2112	92.1	27.4	16.5
30.3734.0-003 CANADIAN SOLAR CS6K-295MS	7845	2078	90.7	31.4	16.2

Table 7 Results at tilt of 35º (23/03/2021).

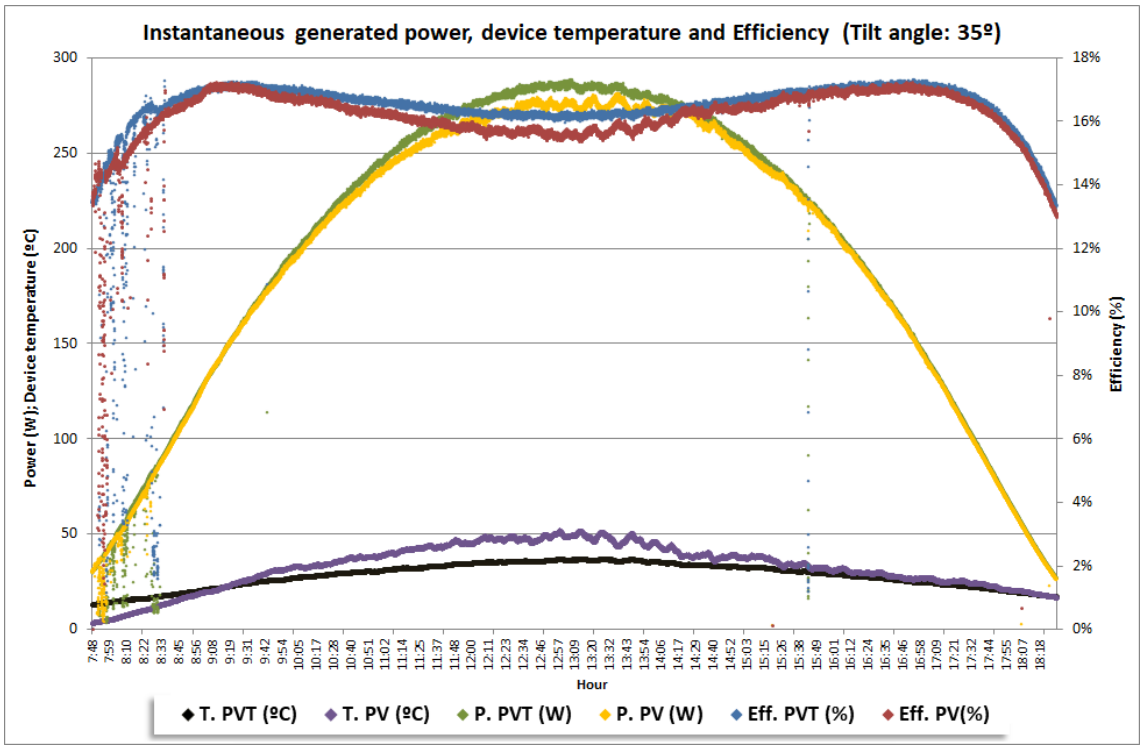

Figure 12 Comparative graph of electrical performance at tilt of 35º (23/03/2021).

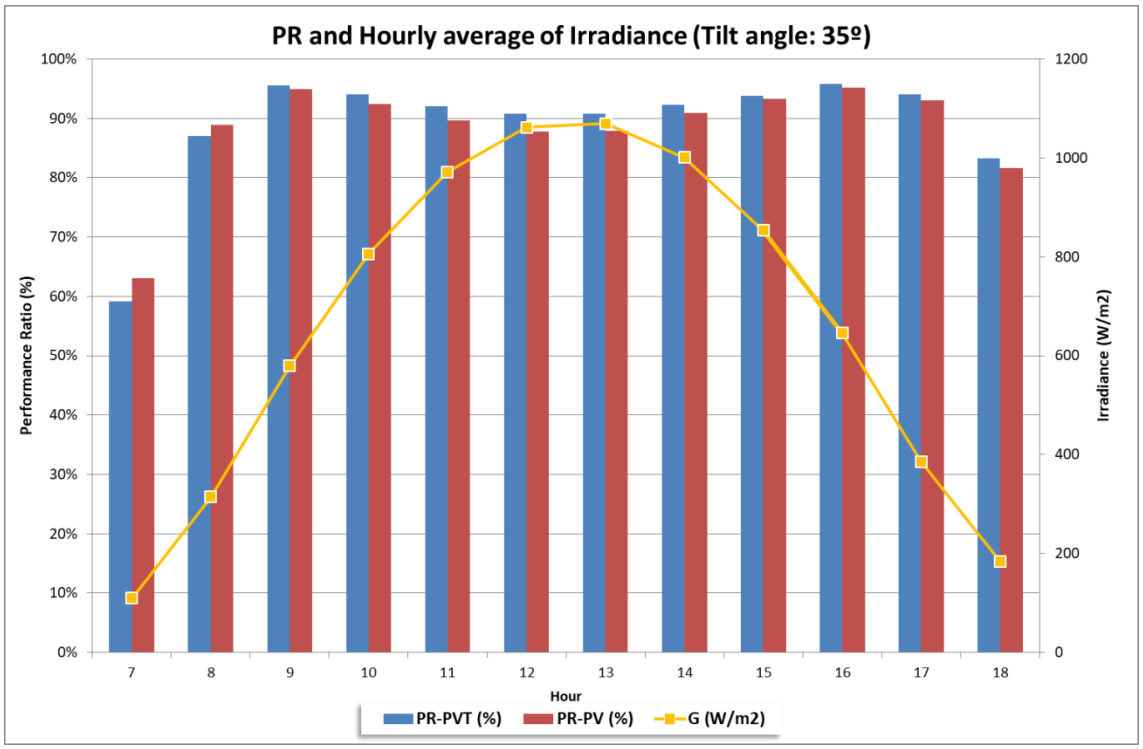

Figure 13 Comparative graph of PR at tilt of 35º (23/03/2021).

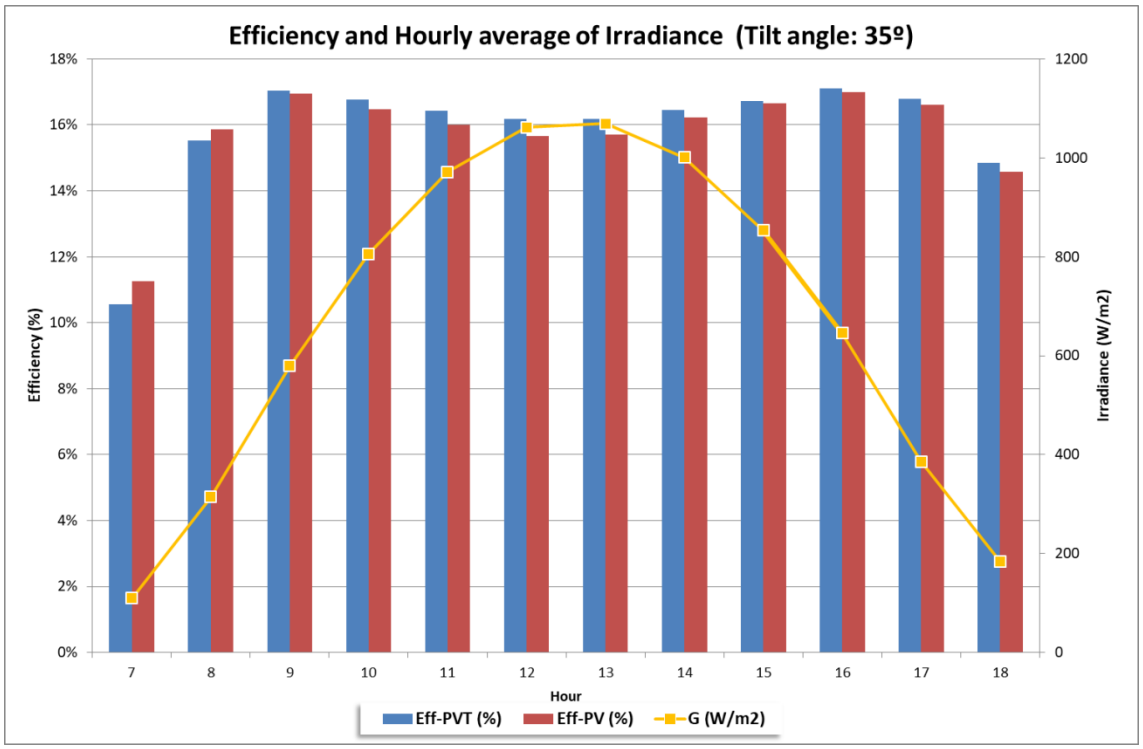

Figure 14 Comparative graph of Efficiency at tilt of 35º (23/03/2021).

Following, summary results of PR and Efficiency for both tilts are presented in next table.

Sample	Tilt: 5º Date: 24/03/2021 Measurement Period: 10.25 h		Tilt: 35º Date: 23/03/2021 Measurement Period: 10.75 h	
	Performance Ratio PR (%)	Device Efficiency η (%)	Performance Ratio PR (%)	Device Efficiency η (%)
30.3734.0-001 FEGEN PVT CSK6-16PS	94.4%	16.9%	92.1%	16.5%
30.3734.0-003 CANADIAN SOLAR CS6K-295MS	91.8%	16.4%	90.7%	16.2%

Table 8 Summary results of PR and Efficiency for a full day.

The main conclusions shown in this study are following exposed:

- Related to the location where these tests are performed, for the two tilts used (5º and 35º) higher values of irradiation and energy production were reached at tilt of 35º for both devices (PV and PVT) in the considered measurement time period on each device, as could be expected.
- From a general point of view and considering the specific test conditions for both cases under study (tilt of 5º and 35º), daily values of energy production, PR and efficiency are better in the PVT device. Improvement of PVT device versus PV device in energy production is in the range of 25 Wh/day to 34 Wh/day, improvement of PR is in the range of 1.5% to 3% and improvement of efficiency is in the range of 0.3% to 0.5%.
- In the same way, the behavior and effect of the temperature in the energy production are consistent with expected values for both devices. Comparing them, in the moments of higher differences of temperatures, higher differences of energy, PR and efficiency are obtained; around 5% in PR and 0.8% in efficiency. For all the test conditions performed in the measurement period, the energy production, PR and efficiency values were always better in the PVT device compared to the PV device.

These conclusions can only be applied to the samples tested, same location and meteorological conditions of the day and time of the test.