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NATIONAL RENEWABLE ENERGY CENTRE

ADItech CORPORACIÓN TECNOLÓGICA

# Report: 30.3734.0-02-EN

# COMPARATIVE PHOTOVOLTAIC PERFORMANCE TESTS PVT COLLECTOR vs. PV MODULE

PHOTOVOLTAIC SOLAR ENERGY DEPARTMENT

**NATIONAL ENERGY RENEWABLE CENTRE (CENER)**

| | |
|---|---|
| **Title:** | COMPARATIVE TESTS PVT COLLECTOR vs. PV MODULE |
| **Code:** | 30.3734.0-02-EN |
| **Report Emission Office:** | Pamplona |

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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 summer 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 PV module and the PVT have been electrically characterized and with 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.

| ID SAMPLE MANUFACTURER MODEL | Tilt 5º | | Tilt 35º | |
|---|---|---|---|---|
| | Performance Ratio (PR) (%) | Device Efficiency η (%) | Performance Ratio (PR) (%) | Device Efficiency η (%) |
| 30.3734.0-001 FEGEN PVT CSK6-16PS | 89.6% | 16.0% | 88.4% | 15.8% |
| 30.3734.0-003 CANADIAN SOLAR CS6K-295MS | 87.6% | 15.6% | 88.1% | 15.7% |

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

- For 5º of tilt degree, PR and efficiency of PVT collector is clearly higher than PV device. For the total period of measurement, PR of PVT collector is 2% higher than PR of PV devices, and efficiency of PVT collector is 0.4% higher than efficiency of PV device.
- In the same case of 5º of tilt degree, approximately from 11:30h in the morning temperature of PV device started to rise in a greater way than PVT collector. The effect

over the electric generated power is noted from this moment, being this effect greater between 14:00h and 17:00h. In average hourly values, the most difference in PR and efficiency was obtained at 15:00h (PR: 89.5% vs 85.9%; efficiency: 16.0% vs. 15.3%)

- For 35º of tilt degree, behavior of the PVT collector is practically identical to PV device. Values of PR and efficiency of PVT collector are better than PV device, but only in a slight way.
- For 35º of tilt degree case, differences between the measured temperatures of both devices are lower than 5º of tilt degree case. In fact, in the afternoon both temperatures become identical.

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

- No significant changes are observed in the electrical parameters of the PV module and the PVT. The maximum power values show a decrease of 0.2% in both samples.
- No new defects are detected in the EL images of both samples after the exposure. The defects observed in the previous characterization remain unchanged.

# 2 TECHNICAL REPORT

## 2.1 SAMPLES DESCRIPTION

| REFERENCE DATA | | | |
|---|---|---|---|
| Number of samples | | 2 | |
| Reception date of samples | | 25/05/2020 | |
| Test period | | 25/08/2020 – 26/08/2020 | |
| **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 | PV thermal module | 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).

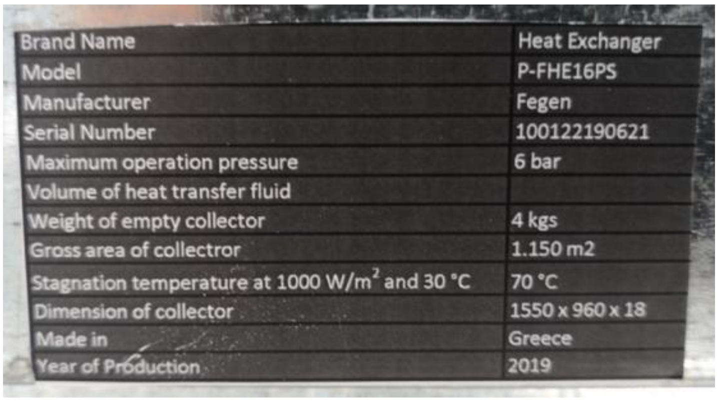




**Figure 1** Marking of CS6K-295MS model (standard module) and PVT marking

**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<br>DATE | T | IRRAD. | $P_{MAX}$ | $I_{SC}$ | $V_{OC}$ | $I_{MP}$ | $V_{MP}$ | FF |
| 30.3734.0-001-MQT06.1FCEM-R002 | 11810481170589<br>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<br>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 (initial)

**AFTER EXPOSURE**

| TEST RESULTS | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| TEST NUMBER | SERIAL NUMBER<br>DATE | T | IRRAD. | $P_{MAX}$ | $I_{SC}$ | $V_{OC}$ | $I_{MP}$ | $V_{MP}$ | FF |
| 30.3734.0-001-MQT06.1FCEM-R003 | 11810481170589<br>08/09/2020 | 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-R003 | 11810481170711<br>08/09/2020 | 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% |

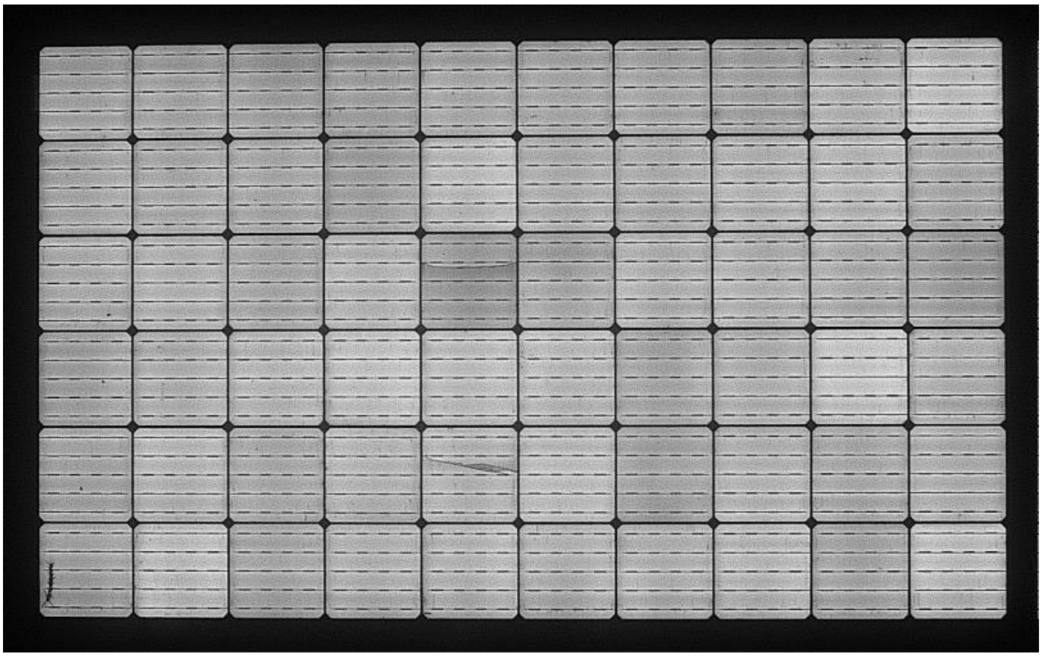
**Table 3** Performance at STC results (after exposure)

## 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-R002 | 11810481170589 | 02/06/2020 | 9.75 A | 0.92 A |

**TEST RESULTS**



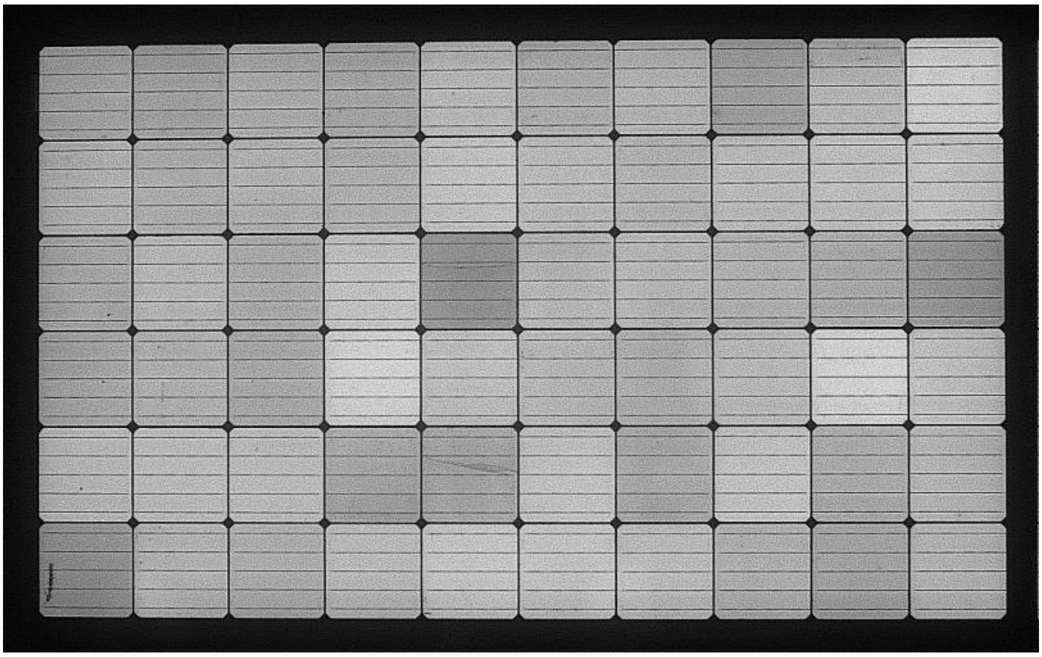
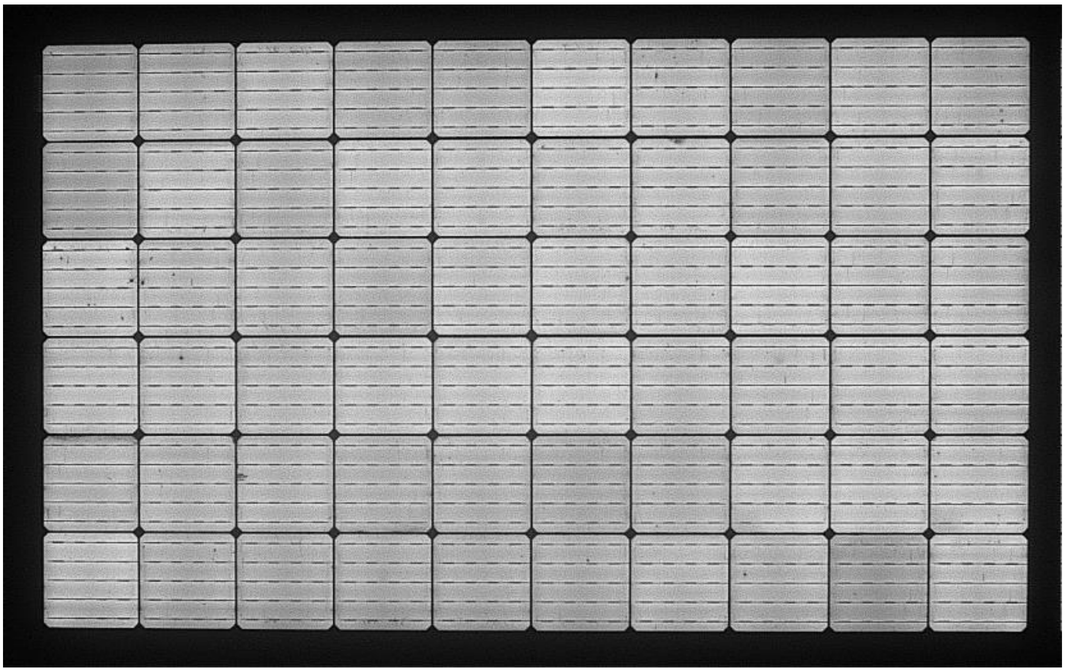


**Figure 3** High-biasing and low-biasing electroluminescence of module 30.3734.0-001

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

**TEST RESULTS**



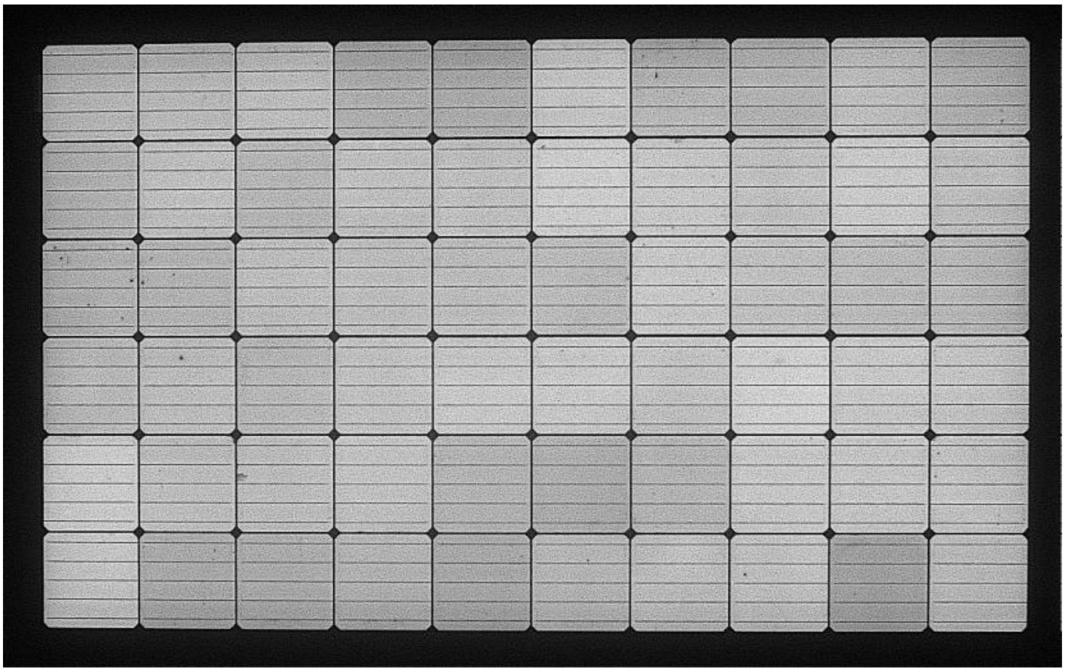
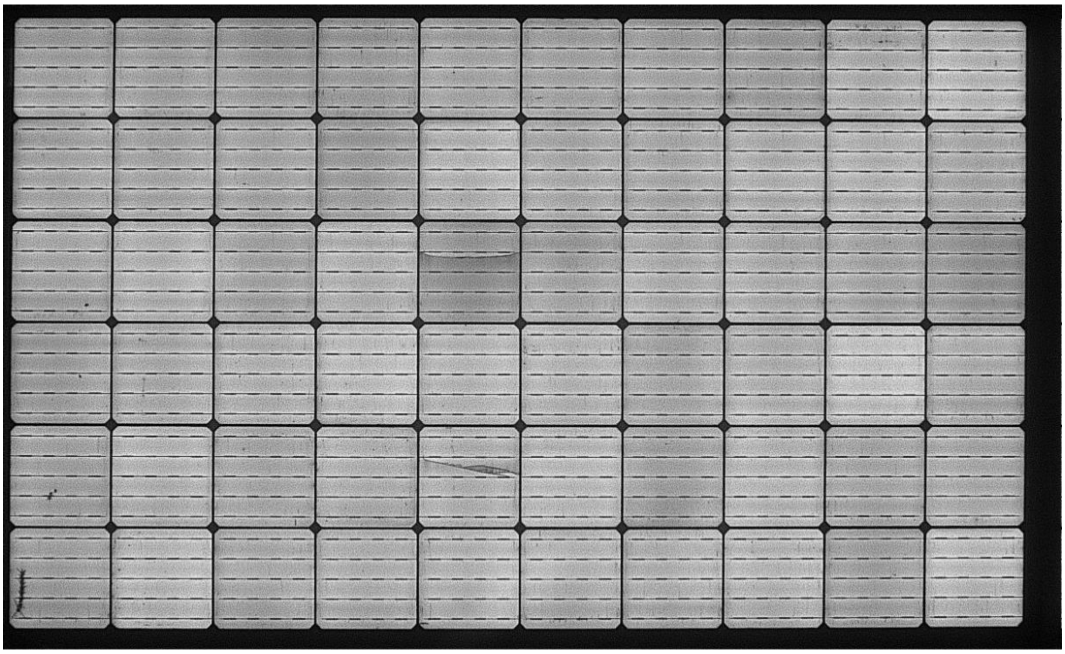


**Figure 4** High-biasing and low-biasing electroluminescence of module 30.3734.0-003

**AFTER EXPOSURE**

| TEST PARAMETERS | | | | |
|---|---|---|---|---|
| TEST NUMBER | SERIAL NUMBER | DATE | $I_{APPL.1}$ | $I_{APPL.2}$ |
| 30.3734.0-001-EL.02ELDP-R003 | 11810481170589 | 07/09/2020 | 9.75 A | 0.92 A |

**TEST RESULTS**



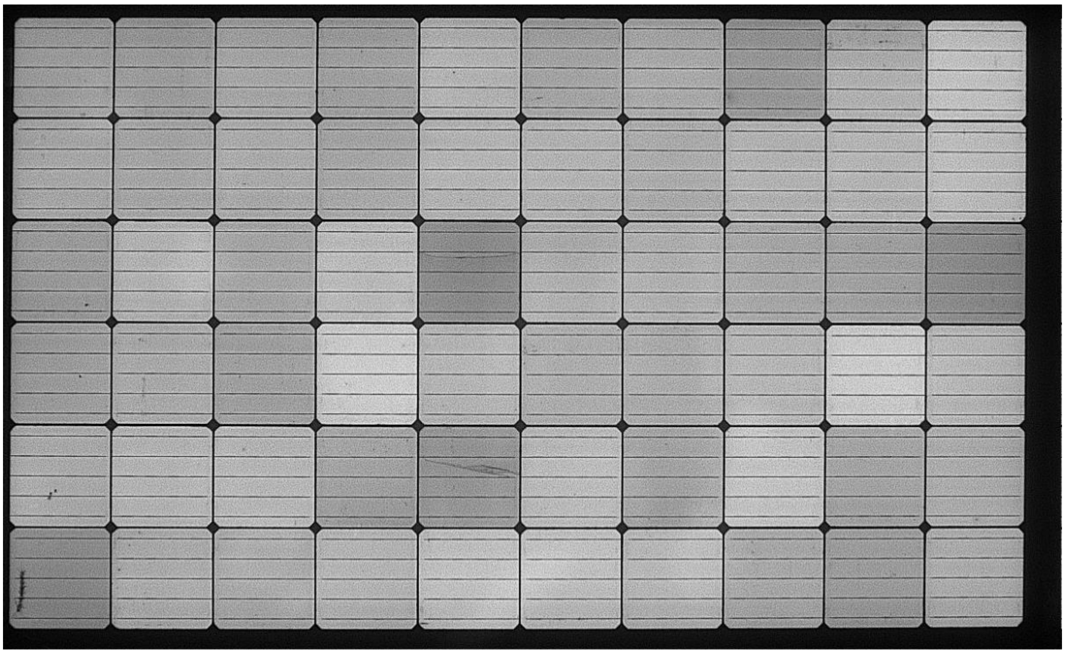
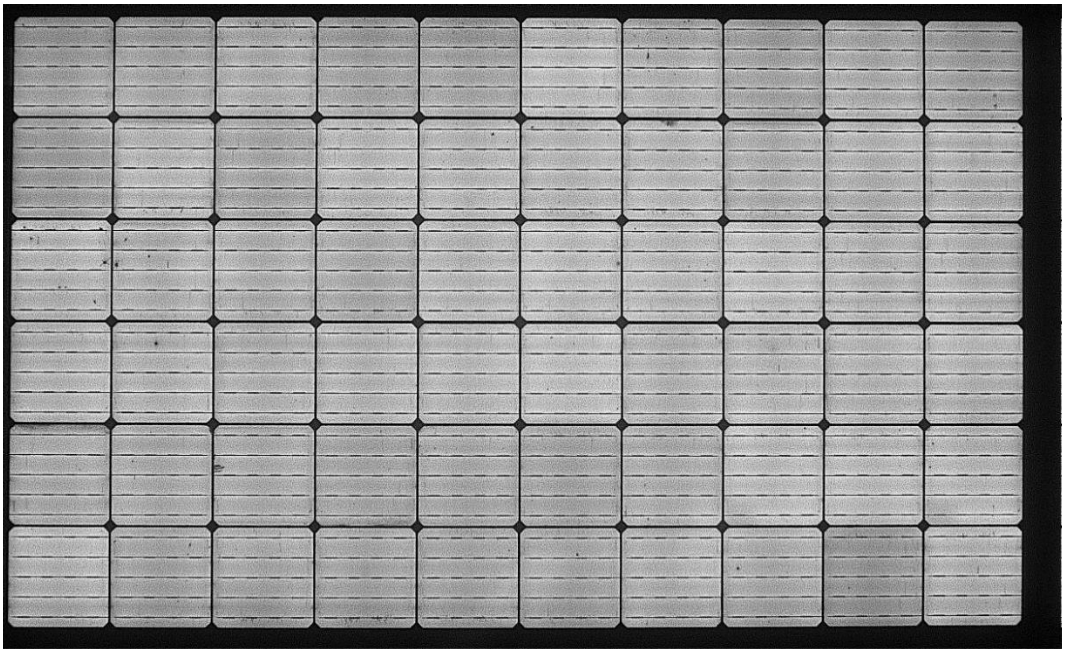


**Figure 5** High-biasing and low-biasing electroluminescence of module 30.3734.0-001

| TEST PARAMETERS | | | | |
|---|---|---|---|---|
| TEST NUMBER | SERIAL NUMBER | DATE | $I_{APPL.1}$ | $I_{APPL.2}$ |
| 30.3734.0-003-EL.02ELDP-R003 | 11810481170711 | 07/09/2020 | 9.75 A | 0.92 A |

**TEST RESULTS**



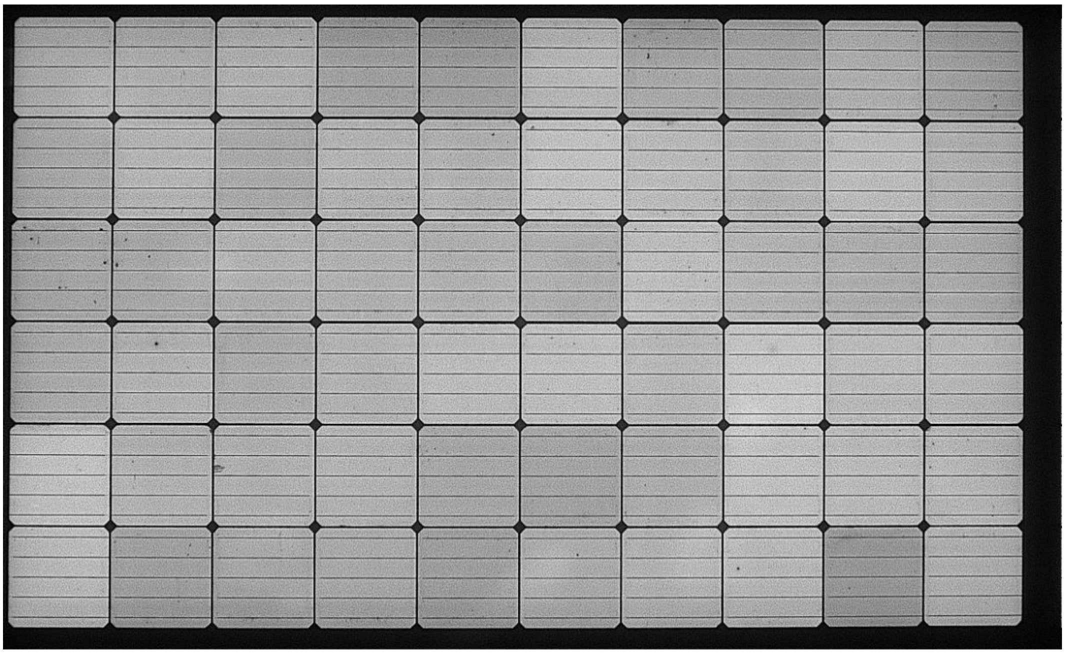


**Figure 6** High-biasing and low-biasing electroluminescence of module 30.3734.0-003

## 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 values show a variation of -0.2%.

### ELECTROLUMINESCENCE CHARACTERIZATION

After the exposure, no new defects are detected in the EL images of both modules. The defects observed in the previous 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.

**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 was made during summer season (25th and 26th of August) 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.

## 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.

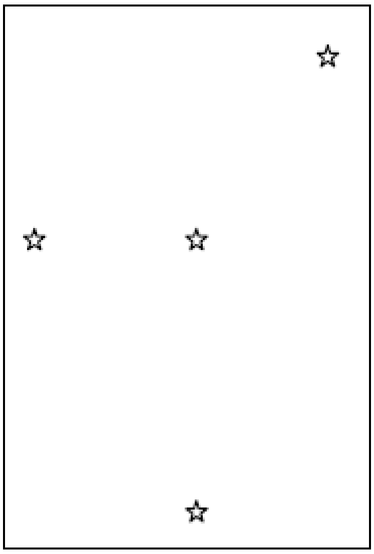


**Figure 8** Temperature probes placement at the rear side of the device, according to IEC 60904-10.

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

| Day 25/08/2020 – Tilt 5º | | | | |
|---|---|---|---|---|
| Time Period 9:10:34 19:59:59 | Irradiance G (W/m$^2$) | Ambient Air Temperature (°C) | PV Module Device Temperature (°C) (30.3734.0-001) | PVT Collector Device Temperature (°C) (30.3734.0-003) |
| **Min.** | 80.5 | 16.7 | 19.2 | 25.0 |
| **Max.** | 940.6 | 36.2 | 62.2 | 46.3 |

**Table 4** Data at tilt angle of 5º (25/08/2020).

| Day 26/08/2020 – Tilt 35° | | | | |
|---|---|---|---|---|
| Time Period 9:10:34 19:59:59 | Irradiance G ($W/m^2$) | Ambient Air Temperature (°C) | PV Module Device Temperature (°C) (30.3734.0-001) | PVT Collector Device Temperature (°C) (30.3734.0-003) |
| **Min.** | 57.2 | 20.2 | 20.8 | 25.4 |
| **Max.** | 1024.6 | 31.7 | 58.7 | 47.8 |

**Table 5** Data at tilt angle of 35º (26/08/2020).

## 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.

| Tilt 5° – Day 25/08/2020; Time Period: 9:10:34 – 19:59:59 | | | | | |
|---|---|---|---|---|---|
| **Sample** | **Solar irradiation H (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.** | 6950 | 1820 | 89.6% | 39.2 | 16.0% |
| **30.3734.0-003 CANADIAN SOLAR CS6K-295MS** | 6950 | 1780 | 87.6.% | 45.7 | 15.6% |

**Table 6** Results at tilt angle of 5º (28/05/2020).

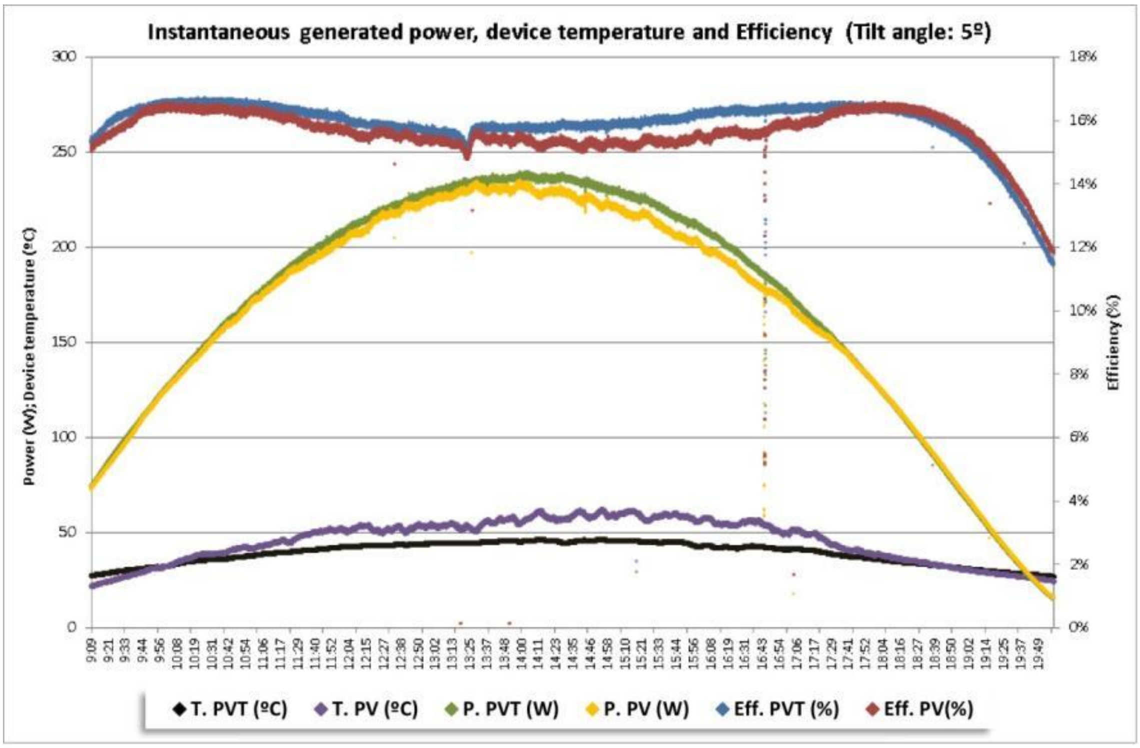



**Figure 9** Comparative graph of electrical performance at tilt angle of 5º (25/08/2020).

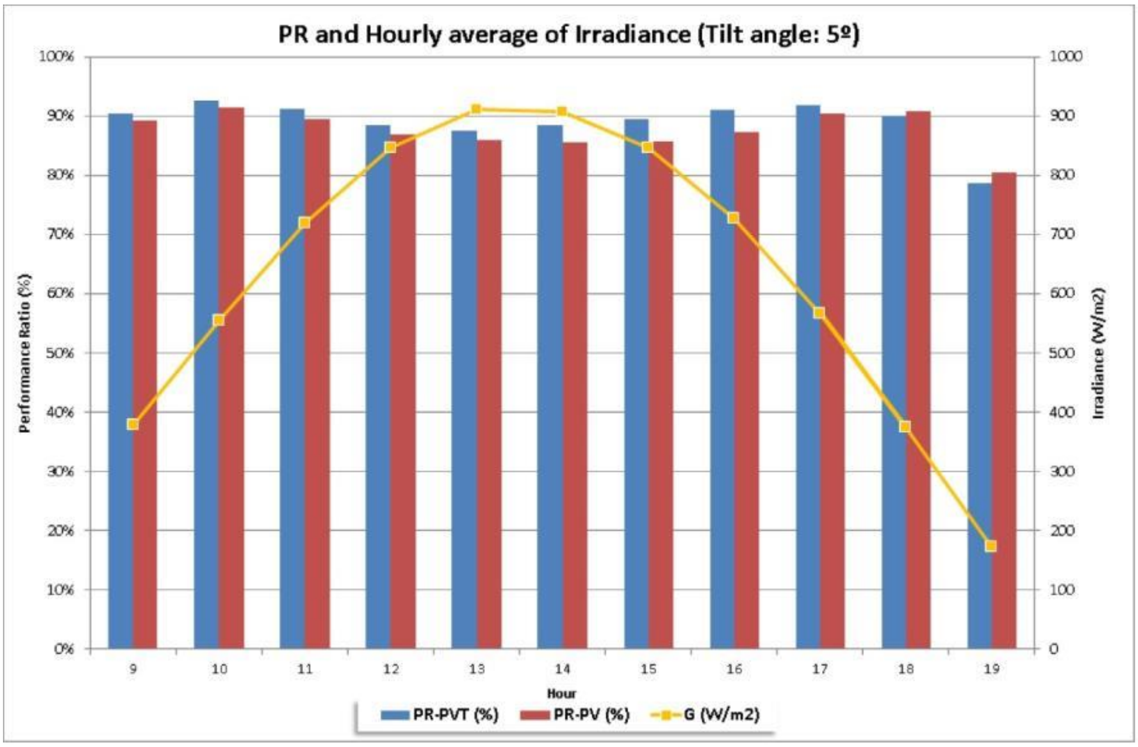



**Figure 10** Comparative graph of PR at tilt angle of 5º (25/08/2020).

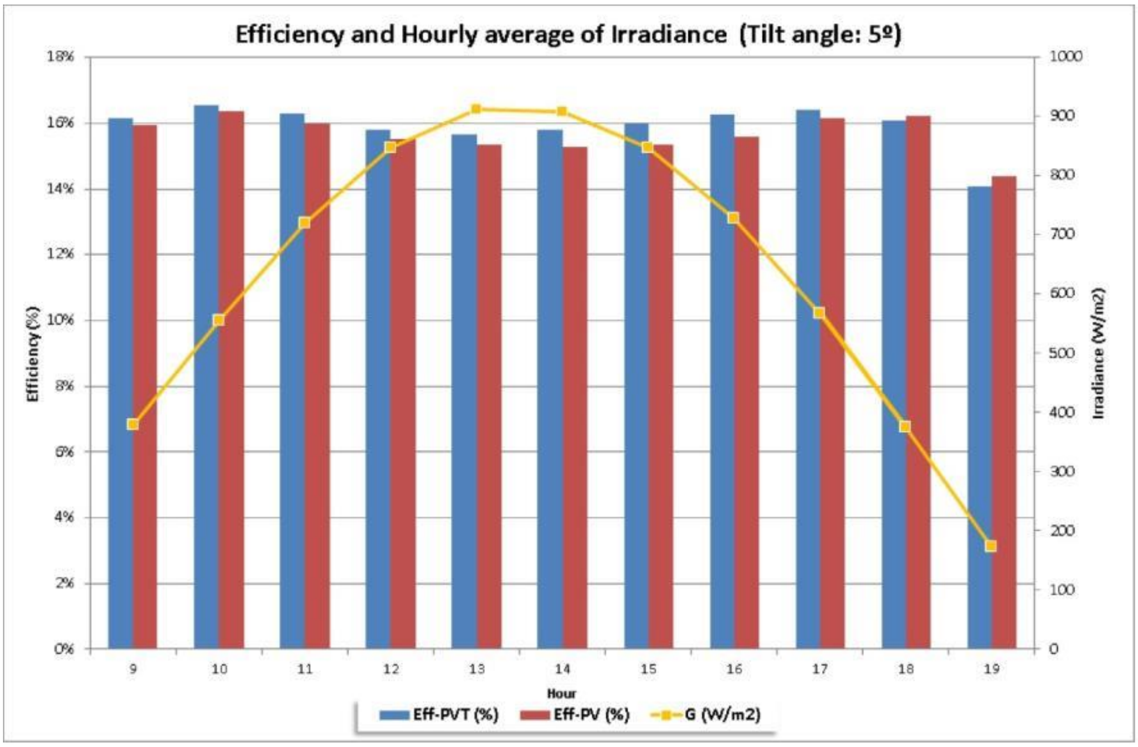



**Figure 11** Comparative graph of Efficiency at tilt angle of 5º (25/08/2020).

| Tilt 35° – Day 26/08/2020; Time Period: 9:10:34 – 19:59:59 | | | | | |
|---|---|---|---|---|---|
| **Sample** | **Solar irradiation H (Wh/m²)** | **Energy production E (Wh)** | **Performance Ratio PR (%)** | **Average Device Temperature (°C)** | **Device Efficiency η (%)** |
| **30.3734.0-001 FEGEN PVT CSK6-16PS.** | 7471 | 1990 | 88.4% | 40.1 | 15.8% |
| **30.3734.0-003 CANADIAN SOLAR CS6K-295MS** | 7471 | 1923 | 88.1% | 43.0 | 15.7% |

**Table 7** Results at tilt angle of 35º (26/08/2020).

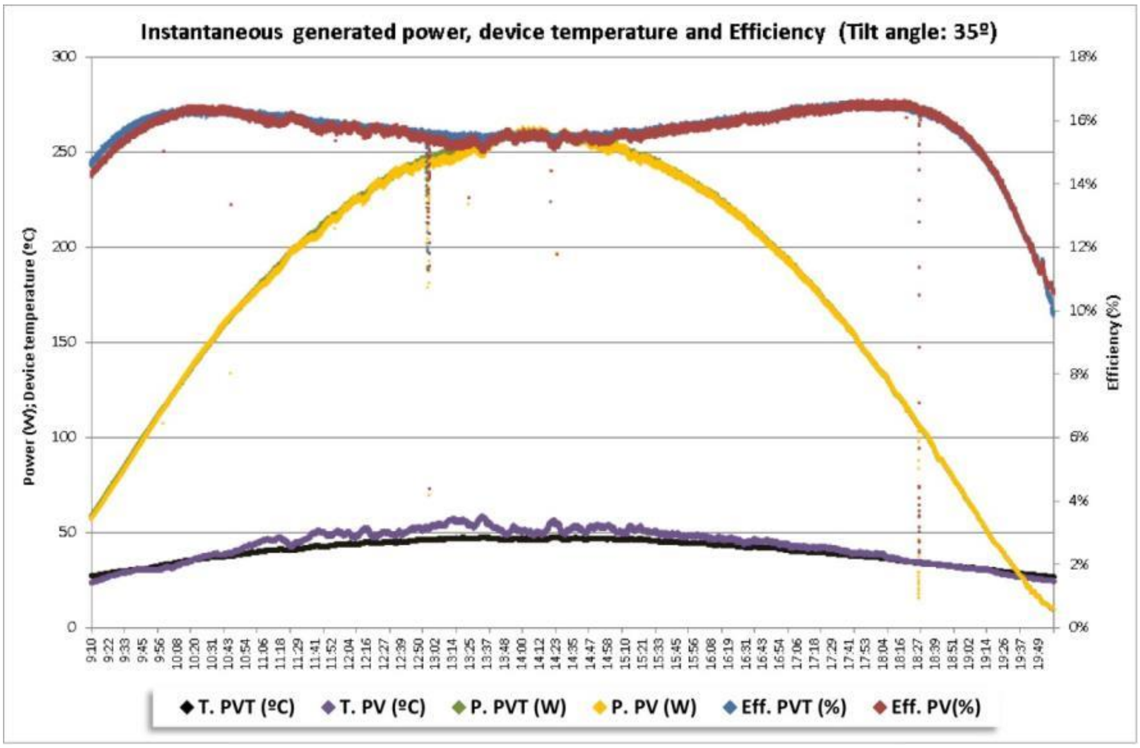



**Figure 12** Comparative graph of electrical performance at tilt angle of 35º (26/08/2020).

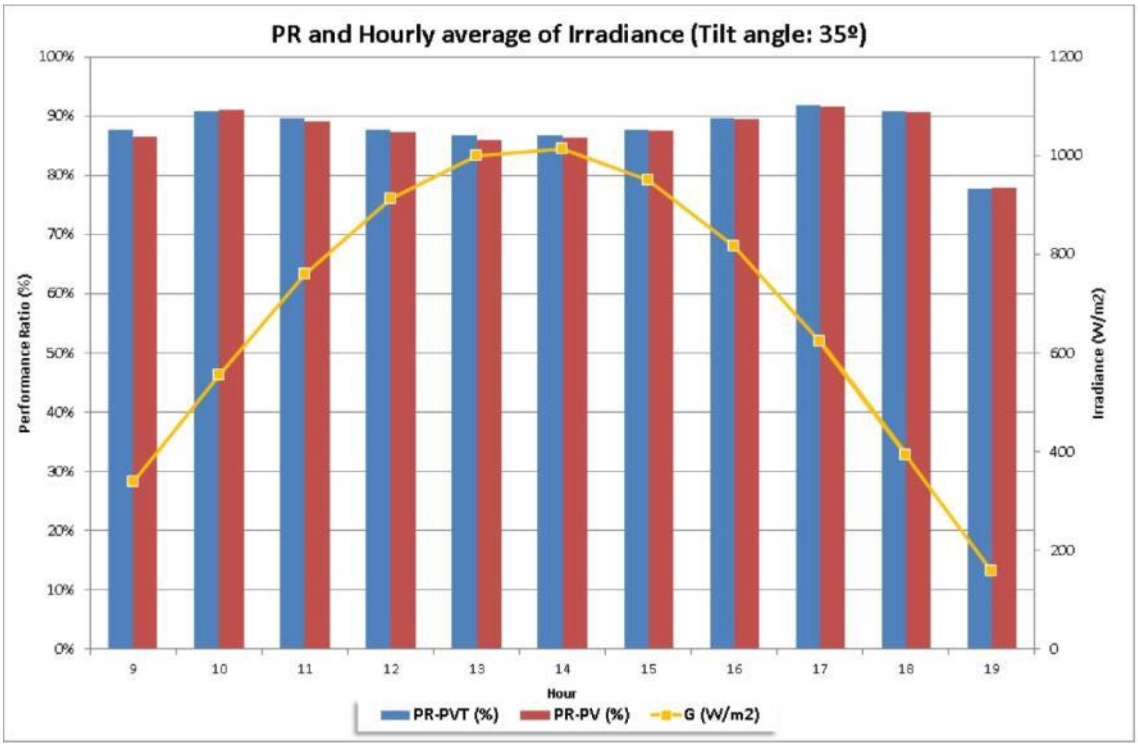



**Figure 13** Comparative graph of PR at tilt angle of 35º (26/08/2020).

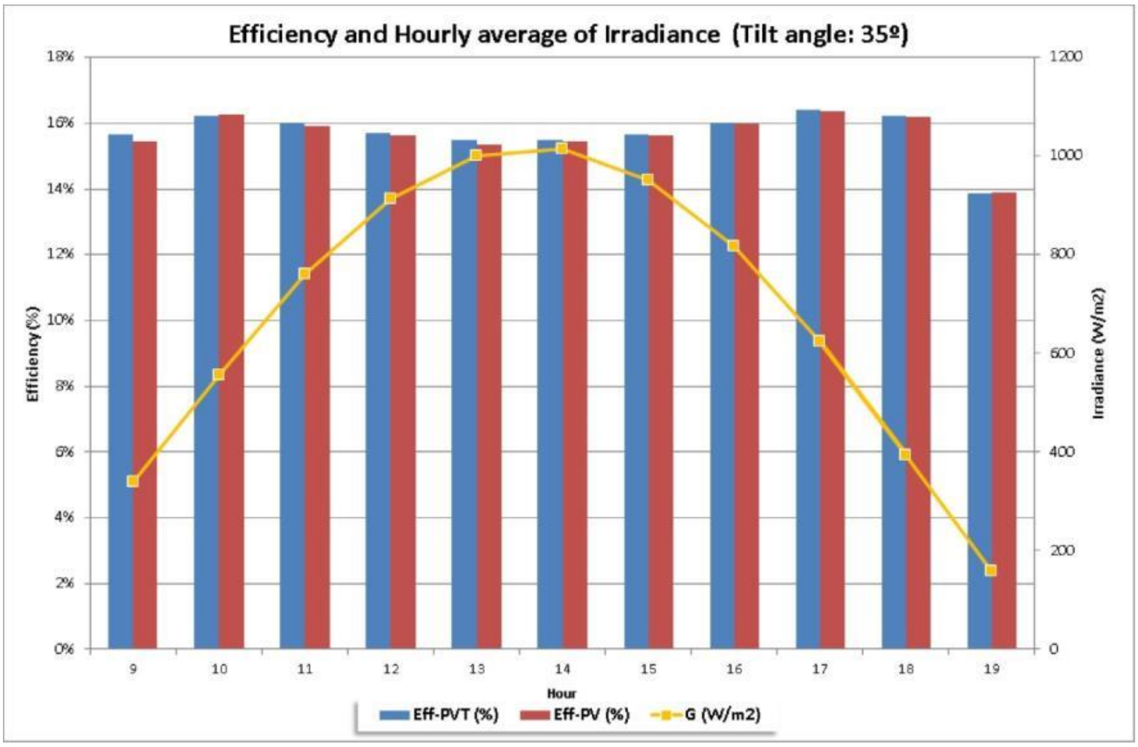



**Figure 14** Comparative graph of Efficiency at tilt angle of 35º (26/08/2020).

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

| Sample | Tilt: 5º | | Tilt: 35º | |
|---|---|---|---|---|
| | Performance Ratio PR (%) | Device Efficiency η(%) | Performance Ratio PR (%) | Device Efficiency η(%) |
| 30.3734.0-001 FEGEN PVT CSK6-16PS. | 89.6% | 16.0% | 88.4% | 15.8% |
| 30.3734.0-003 CANADIAN SOLAR CS6K-295MS | 87.6% | 15.6% | 88.1% | 15.7% |

**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 done, higher values of irradiation and energy production are reached at 35º of tilt degree for the considered measurement time period for both devices.
- For 5º of tilt degree, PR and efficiency of PVT collector is clearly higher than PV device. For the total period of measurement, PR of PVT collector is 2% higher than PR of PV devices, and efficiency of PVT collector is 0.4% higher than efficiency of PV device.
- In the same case of 5º of tilt degree, approximately from 11:30h in the morning temperature of PV device started to rise in a greater way than PVT collector. The effect over the electric generated power is noted from this moment, being this effect greater between 14:00h and 17:00h. In average hourly values, the most difference in PR and efficiency was obtained at 15:00h (PR: 89.5% vs 85.9%; efficiency: 16.0% vs. 15.3%)
- For 35º of tilt degree, behavior of the PVT collector is practically identical to PV device. Values of PR and efficiency of PVT collector are better than PV device, but only in a slight way.
- For 35º of tilt degree case, differences between the measured temperatures of both devices are lower than 5º of tilt degree case. In fact, in the afternoon both temperatures become identical.

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