# INFRARED THERMOGRAPHY AS AN ESTIMATOR TECHNIQUE OF A PHOTOVOLTAIC MODULE PERFORMANCE VIA OPERATING TEMPERATURE MEASUREMENTS

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**Abstract**

The importance of a photovoltaic cell/module operating temperature for its electrical performance is well known, as well as the necessity for in situ fast and reliable monitoring techniques for PV park efficiency. Nowadays, these techniques are based namely on conventional “data acquiring” measuring principles. The latter are time consuming and unreliable in case of not suitable and uncertified measuring equipment. The challenge for an in situ reliable, fast and adequately accurate technique for the estimation of a PV module performance is more than obvious. The current paper investigates the pertinent correlation among the operating temperature of a PV module in situ ($T_c$) measured by an infrared (IR) camera and its relative electrical performance. The advantages and disadvantages of the (IR) technique are discussed in an effort to facilitate the monitoring/maintenance process in solar energy applications.

*Keywords: Infrared monitoring, photovoltaic performance, PV operating temperature*

## 1. Introduction

Zero-defect manufacturing and production is today’s aspiration for either a single investor or a whole industry. Defects and especially cracks in the materials of structural systems’ components can be crucially detrimental to functional performance and their detection is essential to ensure optimum and secure operation of equipment [1]. Photovoltaic (PV) systems are not an exception to the latter. For PV systems, around 70% of the capital costs are related to the PV modules [2]. Therefore, the payback time of an integrated PV system is mainly determined by the initial power output, power degradation and the lifetime of the module. Guaranteed, certified quality and operation of PV modules is a fundamental requirement which provides the basis for the profitability and security of the investment. In other words, there is a strong need to reduce any source of dysfunction of a PV module, generally due to surface defects, i.e. discontinuities and cracks.

Among different condition monitoring methods and non-destructive testing techniques available, infrared (IR) thermography is seen as a promising technique for fast, reliable inspection and defect detection [3]. Infrared (IR) thermography is a two-dimensional non-destructive technique that utilizes the radiation in the infrared range of the electromagnetic spectrum (approximately 0.9–14 μm) to produce images of a specific temperature pattern. According to the Planck’s black body radiation law, infrared radiation is emitted by all objects and it is proportional to their temperatures. Hence, IR thermography makes it possible to determine the surface temperature and, consequently, any abnormalities to the temperature pattern of the inspected equipment. This information, together with data on the physical construction of the component and the thermodynamic state of the equipment is used to evaluate the degree of deterioration.

There are two different applicable approaches regarding IR thermography, i.e. the passive and the active approach. In passive thermography, the features of interest are naturally at a higher or lower temperature than the background. Abnormal temperature profiles indicate a potential problem, and a key term is *temperature difference* with respect to a reference, often referred to as *ΔT value* or *hot spot*. Generally, passive thermography is rather qualitative since the goal is simply to detect anomalies. On the other hand, in active thermography, it is necessary to conduct some energy the specimen inspected in order to obtain significant temperature differences witnessing the presence of subsurface anomalies [4]. In principle, there are four testing procedures of active thermography, depending on the type of the conducted thermal stimulation:

- Pulsed thermography (short thermal stimulation pulse)
- Step heating thermography (long thermal stimulation pulse)
- Lock-in thermography (thermal wave generation by periodic deposition of heat on a specimen's surface)
- Vibrothermography (mechanical vibrations induced external to the structure, resulting in thermal energy release by friction)

In Table 1, there is a brief overview of the most common applications of both active and passive thermography [4].

**Table 1** Common applications of passive and active thermography

| Passive thermography | Active thermography |
|---|---|
| ▪ Building inspection (moisture evaluation, roofs, thermal insulation, liquid level in tanks)<br>▪ Components/processes (printed-circuit boards, welding, glass industry, etc)<br>▪ Maintenance (bearings, turbine blades, electric installations, pipelines, etc)<br>▪ Medicine<br>▪ Material properties<br>▪ Public services (forest fire detection, road traffic monitoring, etc) | ▪ Components/processes (aircraft structural component inspection, spot welding inspection degradation of EPROMs, etc)<br>▪ Defect detection and characterization (metal corrosion, crack detection, coating wear, disbonding, fatigue tests, etc)<br>▪ Medicine<br>▪ Material properties (thermophysical properties, thermal conductivity, anisotropic material characterization) |

## 2. Theoretical Background

### *2.1 Introductory notes*

As an energy-related application, photovoltaics are strongly related to heat transfer. Heat transfer refers to the devolvement of thermal energy from a higher-temperature object to a lower one, as described by the second law of thermodynamics. When a solid or a fluid is at a different temperature than its surroundings or another object, transfer of thermal energy, also known as heat transfer, or heat exchange, takes place in such a way that they reach thermal equilibrium. Heat transfer occurs by three basic mechanisms, i.e. conduction (within solids), convection (between a solid surface and a fluid) and radiation (between two solids).

It can be said that, IR thermography is an optical method in visualization of heat transfer and temperature distribution helping to explain phenomena such as abnormal temperature pattern. Focusing on the aforementioned heat transfer mechanisms, this paper presents an effort that has been made to assess experimentally the prospects of the deployment of infrared thermography as a practical performance estimator technique for PV modules, via operating temperatures, i.e. correlating the thermographically measured operating temperatures ($T_{measured}$) with the expected ones ($T_{expected}$). The estimation of $T_{expected}$ can be based on the analysis of a PV module thermodynamic model.

### *1.2 Thermodynamic model aspects*

The performance analysis of a PV module can be viewed by an energetic angle as other researchers have already mentioned [5].Two major components contribute to a PV module energy performance, electrical and thermal energy. While solar radiation generates electricity (electrical energy) due to photovoltaic effect, solar cells are also heated via heating dissipation mechanisms. These energy components are completely competitive. While the electrical energy (electricity) can be used for useful purpose, the thermal energy is not utilized and lost to the ambient. However these thermal losses can be used in photovoltaic thermal (PV/T) modules or combined systems.

Figure 1 presents a schematic drawing of a PV panel which is considered as a multi-layer thermodynamic wall. A PV panel is composed of a thick sheet of chemically hardened glass (3 mm), two very thin films of EVA foil (0.25 mm each), the Si-cell matrix (0.5 mm), and the back cover. If the EVA foils, the sealing materials and the frame, are supposed negligible, due to a low surface area, then the PV is composed of three main layers as figure shows.

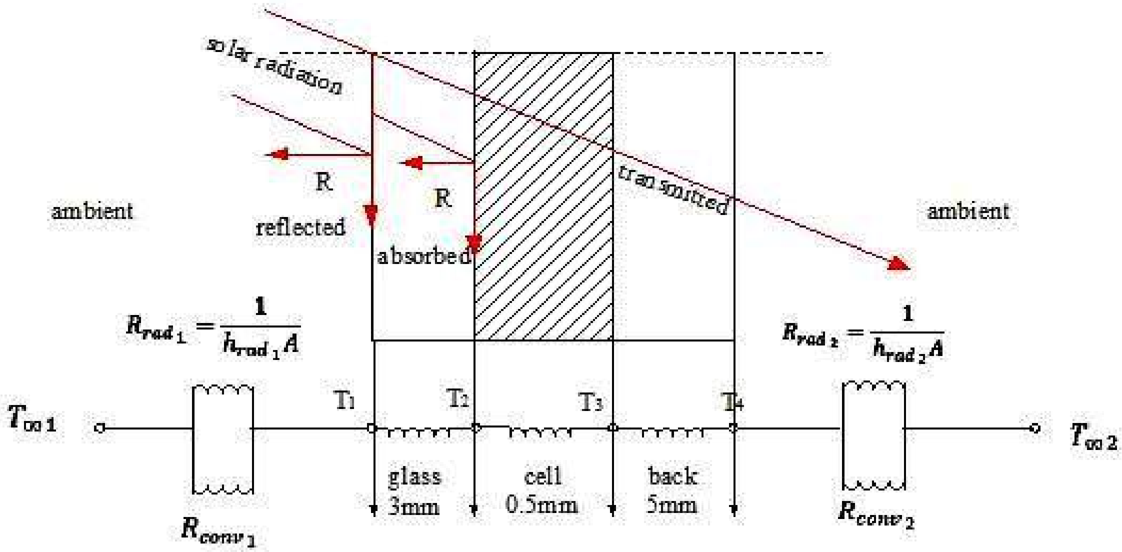


**Figure 1** PV module thermodynamic model

Generally speaking, convection and radiation heat transfer ($\dot{Q}$ , see below) from the front to the back surfaces of the module are considered significant. The energy balance equation for solar cell of a PV module can be written as eq. (1) shows if is assumed that one dimensional heat mechanism is a fair approximation, the glass cover is at uniform temperature, the system is in quasi-steady state and the ohmic losses in the cell and module are negligible:

$$\dot{E}_n = \dot{Q}_{Tca} + \dot{Q}_{Tcbs} + \dot{E}_e \qquad (1)$$

where:

$\dot{E}_n$ : the rate of solar energy available of PV module
$\dot{Q}_{Tca}$ : an overall heat loss from top surface of cell to ambient
$\dot{Q}_{Tcbs}$ : an overall heat transfer from cell to back surface
$\dot{E}_e$ : the rate of electrical energy produced.

An expression for temperature dependence electrical (energy) efficiency of a PV module according to Schott [6], Evans [7] or Skoplaki et. al. [8] is given by:

$$n = n_o\left[1 - 0.0045\left(\overline{T}_c - \overline{T}_a\right)\right] \tag{2a}$$

or according to Zondag et al. [9], the electrical efficiency in exergy terms is:

$$\Psi_e = n_{cell}[1 - 0.0045(T_{cell} - 25^o C)] \tag{2b}$$

where:

$n$ : the PV module energy efficiency (%)
$n_o$ : the electrical efficiency under standard test condition (solar radiation flux $G_T$=1000 W/m², $T_a$=25 °C, wind velocity $V_f \approx$1 m/s)
$\Psi_e$ : the electrical efficiency (%)
$n_{cell}$ : the solar cell efficiency (%)
$T_{cell}$ : the photovoltaic cell temperature (°C)
$T_a$ : the ambient air temperature (°C).

An expression for the total energy $\Psi_{PV}$ (exergy, available electrical and thermal energy) of a PV module according to Joshi et. al. [5] is given by eq. (3):

$$\Psi_{PV} = \frac{V_m I_m \left(1 - \left(\frac{T_{amb}}{T_{cell}}\right)\right) \cdot \dot{Q}}{E_{Xsolar}} \tag{3}$$

where:

$V_m$ : the voltage at maximum (actual) power generation (V)
$I_m$ : the current at maximum (actual) power generation (A)
$T_{amb}$ : the ambient temperature (°K)
$E_{Xsolar}$ : the exergy of solar irradiance (W)

$\dot{Q}$ is defined as the convective and radiative heat transfer according to eq. (4) below:

$$\dot{Q} = h_{ca} A\left(T_{cell} - T_{amb}\right) \tag{4}$$

where $A$ is the PV area (m$^2$) and:

$$h_{ca} = 5{,}7 + 3{,}8 \cdot V_f \tag{5}$$

and according to Skoplaki et. al. [10]:

$$T_{cell} = T_{amb} + \left( \frac{0{,}32}{8{,}91 + 2 \cdot V_f} \right) G_T \tag{6}$$

From the previous equations it is evident that the electrical or in exergy term of total energy efficiency of a PV module is heavily induced by the thermal energy diffused due to solar radiation. If it is assumed that the cell temperature is approximately equal to the module temperature ($T_{cell} \approx T_{module}$) then the knowledge of the latter will help estimating the module efficiency. The thermography approach emerges as a unique tool for the measuring of the module's surface temperature as the current research team presented in a previous work [1].

## 3. Experimental set-up

### *3.1 Hardware and software*

The thermal camera (portable thermal imager) employed for the performed experiments was an Impac IVN 780-P (Figure 2, left). The high resolution IVN model has a temperature range of -40 to +1000 $^{o}$C with an accuracy of 2 $^{o}$C or 2% of reading and an image update rate of 8.5 frames per second with a spectral range of 8 to 14μm long. The experiments concluded three sets of passive (in situ) thermography measurements regarding a non-commercial standalone (under no load) PV module without glass coating (Figure 2, right). The inspected module consists of 20 polycrystalline silicon (p-Si) cells and has a maximum power rating $P_{max}$ of 40 $W_p$, rated current $I_{MPP}$ of 3.6 A and rated voltage $V_{MPP}$ of 11.1 V. Each string of the PV module and each cell were, in principle, considered as linear and orthogonal regions of interest (ROI) during the processing of the thermal images which included ROI, line profile and isotherm analysis and was performed with the Impac MikroSpec 4 Basic software.

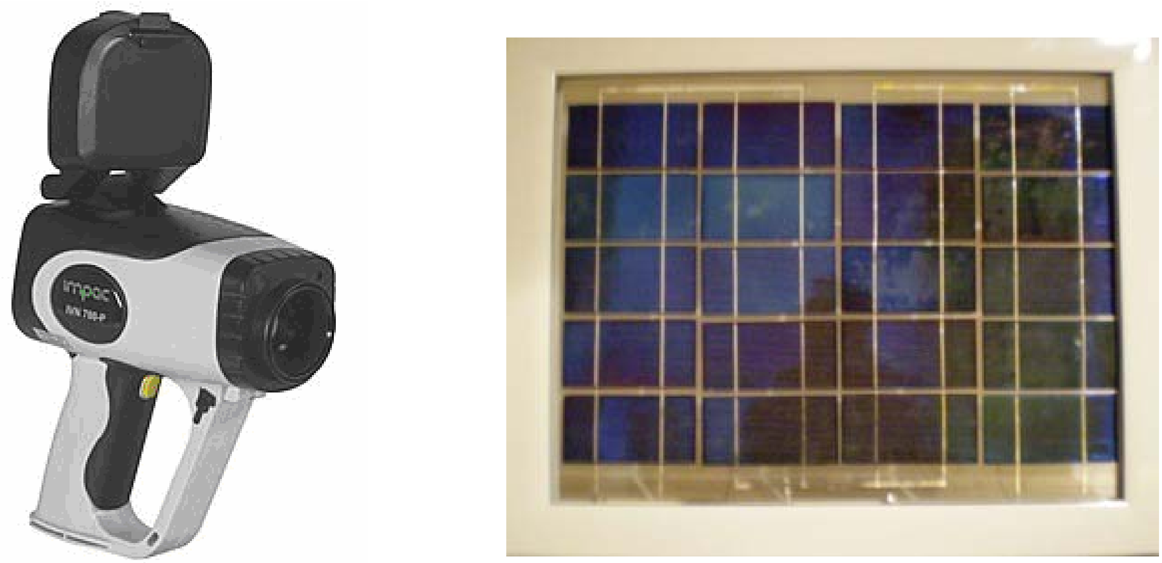

**Figure 2** The portable thermal imager (left) and the non commercial PV module (right) employed for the performed experiments

### *3.2 Experimental outline – Background parameters*

The experimental measurements took place in Xanthi/Thrace (north-eastern Greece, latitude: 41.14°, mean elevation: 40m), on three daily sets, i.e. August 26th, 27th and 29th 2009, under clear sky conditions. Each set included three instant measurements, according to the time; 06:00 (transient conditions - sunrise), 15:00 (steady-state conditions), 20:00 (transient conditions - sunset). For each of these measurements, environmental conditions such as ambient air temperature, humidity, mean value of solar radiation flux $G_T$ and wind speed were taken into account for the set-up of the background parameters of the thermal camera. The whole experimental outline for the three daily sets is given in Table 2.

**Table 2** The experimental outline

| Date | August 26th | | | August 27th | | | August 29th | | |
|---|---|---|---|---|---|---|---|---|---|
| Measurement | 06:00 | 15:00 | 20:00 | 06:00 | 15:00 | 20:00 | 06:00 | 15:00 | 20:00 |
| Ambient air temperature (°C) | 16.5 | 27 | 23.5 | 17.5 | 28 | 24 | 18 | 26 | 23.5 |
| Humidity (%) | 65 | 30 | 60 | 62 | 35 | 55 | 70 | 35 | 60 |
| Wind speed (m/s) | 0.72 | 6.12 | 2.16 | 2.88 | 6.48 | 2.52 | 0.72 | 5.04 | 1.8 |
| $G_T$ ($W/m^2$) | n/a* | 448 | n/a | n/a | 472 | n/a | n/a | 435 | n/a |

*n/a refers to solar radiation flux values under 15 $W/m^2$

## 4. Results - Discussion

The acquired thermal images from the inspected PV module were analyzed in order to generate a simple and fast correlation between the thermodynamic model based temperatures of each solar cell of the module (estimated cell temperature, $T_{ce}$) and the measured temperatures (measured cell temperature, $T_{cm}$) obtained from the in situ thermographic inspection. In practice, any possible significant declination between $T_{ce}$ and $T_{cm}$ will induce an abnormal overall temperature pattern across any problematic region of the PV module's surface.

Figure 3 shows the thermal image of the inspected module on August 26th at 15:00 (steady-state conditions). Each solar cell can be studied as a single orthogonal region of interest, during the preliminary ROI analysis. Applying the eq. (4) for the environmental parameters of this measurement (see Table 2), gives an estimated cell temperature, $T_{ce}$=33.8 °C.

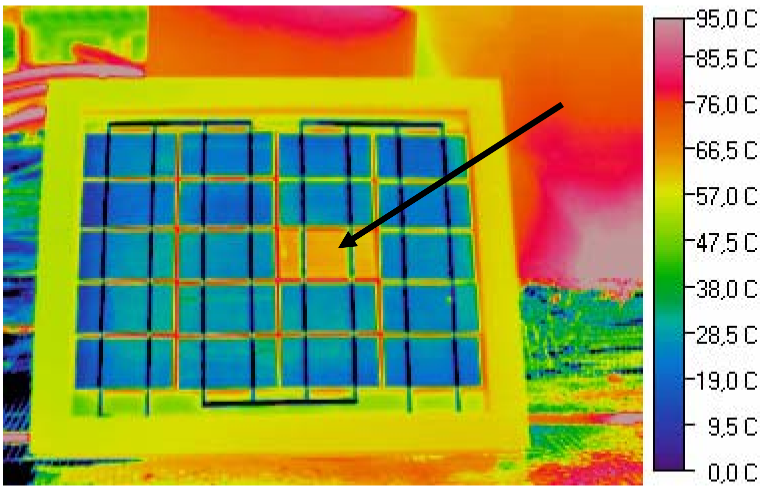


**Figure 3** Thermal image of the inspected PV module on August 26th, at 15:00

Observing Figure 3 with the temperature scale (0-95 $^oC$) and the color palette (rainbow scale), it can be said that the measured temperature $T_{cm}$ values of each "healthy" solar cell of the module fluctuate within the region of 30-32 $^oC$. This small declination between $T_{ce}$ and $T_{cm}$ can be considered as normal, due to possible emissivity factor uncertainties and the fact that the PV module is under no load. Although, there is a possible problem regarding the solar cell that is indicated by the black arrow in the same Figure. The specific cell presents temperature values in the region of 60-66 $^oC$, abnormally higher than the estimated $T_{ce}$ by a $\Delta T > 30$ $^oC$. As a consequence, this cell represents a "hot spot" area through the inspected PV module surface, revealing an implicit defect and, further, a deteriorated module performance.

Isotherm Analysis (IsA), in Figure 4, presents an other view of the above remarks. An "upper" and "under" temperature threshold has been set within the region of the problematic cell's temperatures and it has been typified (contractually) by the black colour. The same process repeated for the "normal cell temperature" and "$\Delta T$" regions applying the white and grey colors respectively. With this technique any problematic cell can be represented by black pattern, standing out from the rest normally operating PV cells.

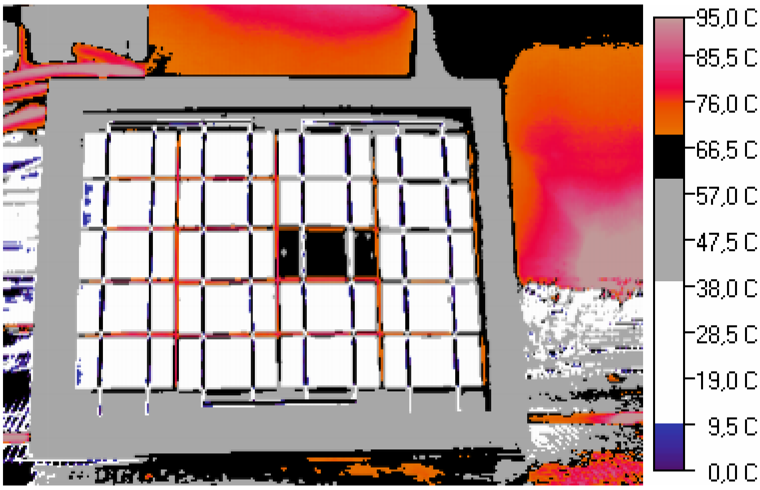


**Figure 4** Isotherm of the inspected PV module on August 26th, at 15:00

Moreover, Line Profile Analysis (LPA) produces graphs by linear ROIs showing the temperature fluctuation (Y axis) across the length of each ROI in pixels scale (X axis). In particular, Figure 5 shows the thermal image with the linear ROIs 1 and 2 (on the left side) and the two generated line profiles 1 and 2 (on the right side).

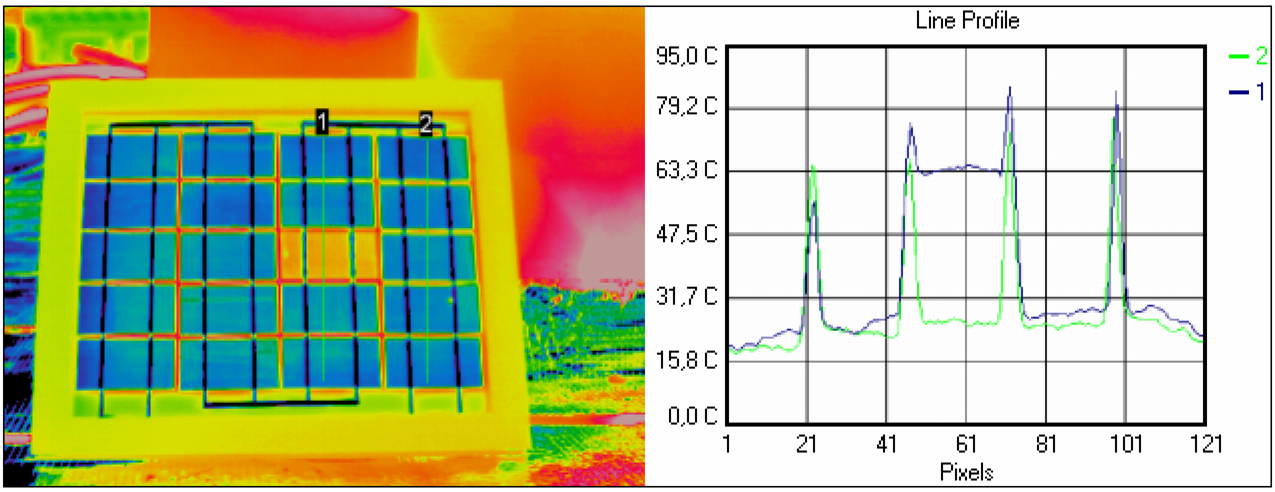


**Figure 5** Line profile analysis the inspected PV module on August 26th, at 15:00

ROI 1 extends across the vertical string of 5 cells that includes the problematic element, while ROI 2 extends representing a vertical string of 5 normally operating cells. As it is reasonable, the two temperature curves 1 and 2 in the graph are following a normal path across the cells of the string, fitting each other almost perfectly, with the exception that, between pixels 50 and 70, they appear having a significant $\Delta T$; i.e. while curve 2 continues in the same way as in previous cells (regarding pixels 1 to 50), curve 1 remains at an abnormally high level of temperature, over (by $\Delta T$) curve 2.

It should be noticed, that the four peaks that are shown, such as that at pixel 21, correspond to the material (PVC) on which the cells are attached and appears between the p-Si made cells. The temperature values for these small "gaps" of PVC shown on the thermal image are oblique because PVC has, obviously, a different value of emissivity factor $\varepsilon$. Specifically, for the requirements of the measurements, the value of $\varepsilon$ was adjusted with the thermal camera settings at 0.65 (for the p-Si regions), while for PVC the right value is $\varepsilon$=0.85-0.90. This difference induces a respectable error that influences the accuracy of the measured temperature values, not only for the PVC regions but for every non-Silicon surface (where $\varepsilon \neq 0.65$). The actual temperature values for the PVC regions are sensibly lower than the measured ones. However, the described error does not affect the needed measurements which are related only with the p-Si cells.

Figure 6 presents the thermal image of the same module, 24 hours later, on August 27$^{th}$ at 15:00. Working in the same way as before, eq. (4) for the new environmental parameters (see Table 2), gives an estimated cell temperature for this measurement, $T_{ce}$=34.9 $^oC$. In this thermal image, the ROIs of the solar cells give measured temperature $T_{cm}$ values of each "healthy" solar cell of the module which fluctuate within the region of 31-33 $^oC$. As it was expected, the solar cell that is indicated by the black arrow appears to be problematic, presenting temperature values in the region of 63-68 $^oC$, significantly higher than the estimated $T_{ce}$ by a $\Delta T > 30$ $^oC$. As it was formerly explained, this cell represents a "hot spot" that implies a potential defect that undoubtedly affects the module performance.

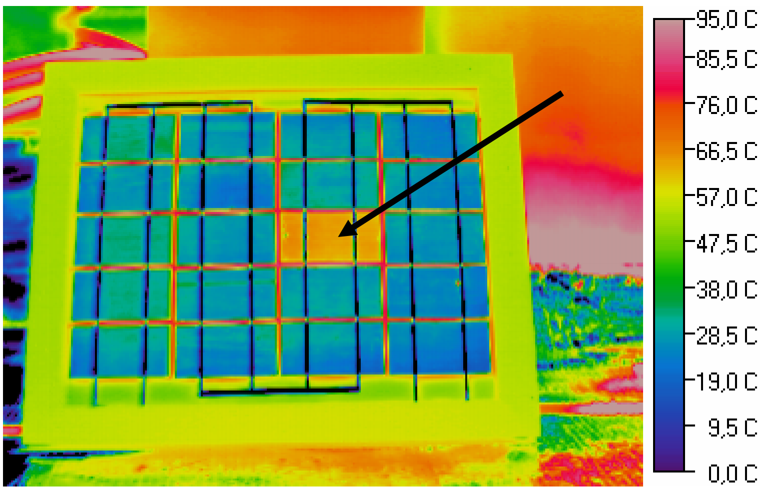


**Figure 6** Thermal image of the inspected PV module on August 27$^{th}$, at 15:00

Both IsA in Figure 7 and LPA in Figure 8 are also used in this measurement to offer two other views of the above observations that contribute to a complete interpretation of what is it seen in the thermal image of Figure 6. Particularly, in the same way as before, in Figure 7 white, black and grey colors are applied to the color/temperature palette typifying the "normal cell temperature", the "suspect cell" and "$\Delta T$" regions of the generated isotherm, in order to highlight the problematic cell with black color. On the other hand, in the line profile of Figure 8, the two temperature curves 1 and 2 (for the linear ROI 1 and ROI 2 respectively) are following a normal path across the cells of the string expect again the region between pixels 50 and 70 where they appear having a significant $\Delta T$, i.e. curve 1 remains at an abnormally high level of temperature, over (by $\Delta T$) curve 2.

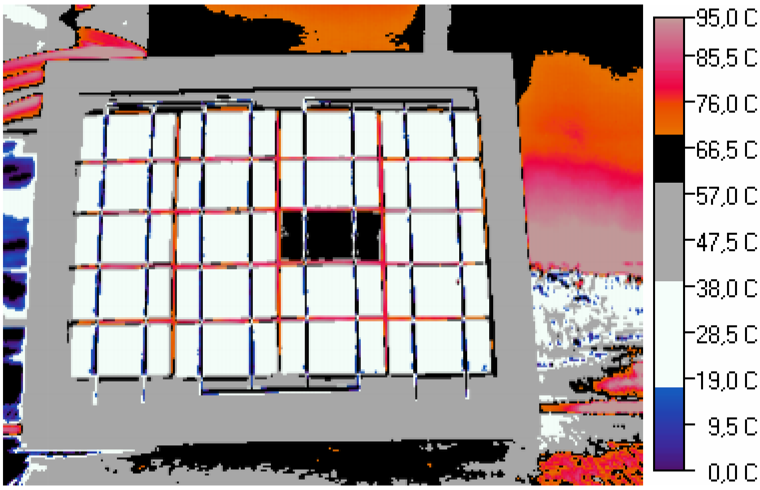


**Figure 7** Isotherm of the inspected PV module on August 27th, at 15:00

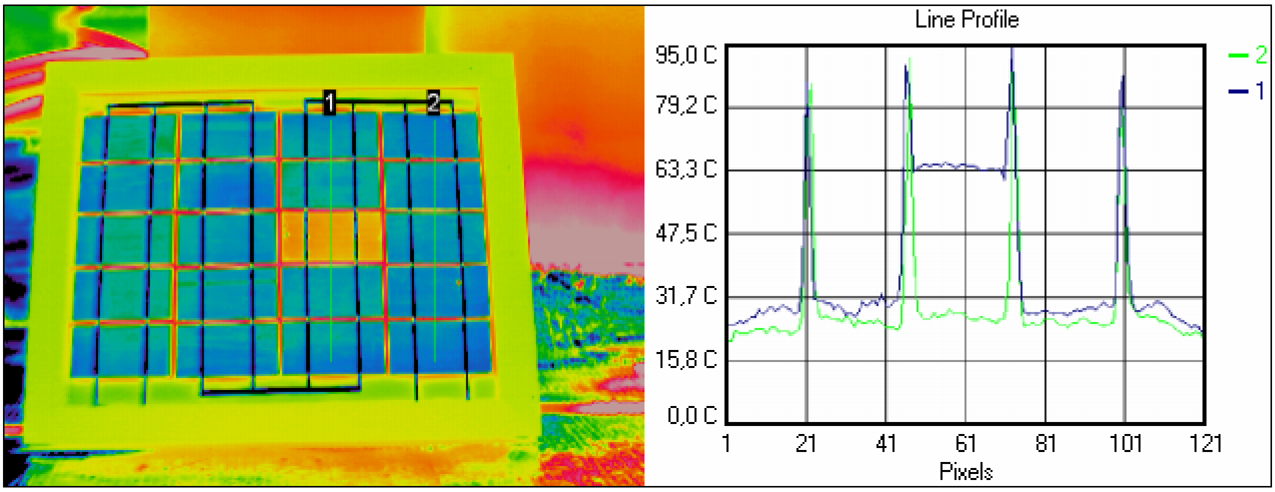


**Figure 8** Line profile analysis the inspected PV module on August 27th, at 15:00

In Figure 9 there is the thermal image of the inspected module, during the third set of measurements, on August 27th, and specifically at 15:00. For this measurement, eq. (4) with the new environmental parameters (see Table 2), gives an estimated cell temperature $T_{ce}$=33.3 $^{o}$C.

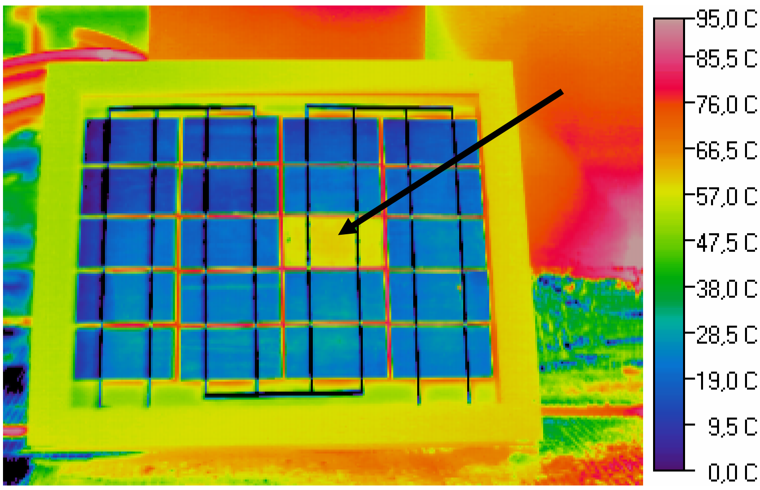


**Figure 9** Thermal image of the inspected PV module on August 29th, at 15:00

Here, in Figure 9, the measured temperature $T_{cm}$ values of each normally operating solar cell of the module, in Figure 9, occur in the region of 30-32 °C. Similarly with Figures 3 and 6, the solar cell that is indicated by the black arrow appears to operate abnormally, presenting temperature values in the region of 59-63 °C, significantly higher than the estimated $T_{ce}$ by a $\Delta T$ almost equal to 30 °C. Finally, IsA in Figure 10 and LPA in Figure 11 are also applied in this measurement in order to give a complete evaluation of the observations in the thermal image of Figure 9.

It would be an omission to not mention that, in this work, the measurements regarding the steady state conditions were preferred from the measurements during sunrise and sunset because in these transient conditions the solar radiation flux gave nearly negligible values. In contrast, steady state conditions helped to make a quite fast and simple correlation between the thermodynamic model of a PV module and the infrared measurements of the inspected module.

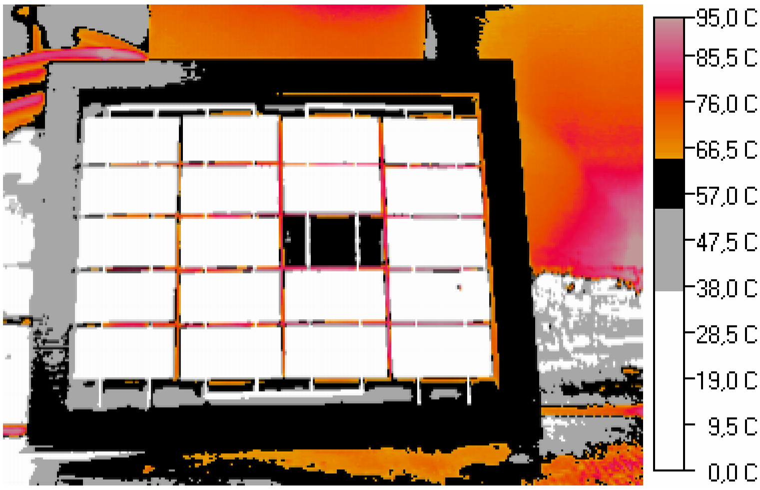


**Figure 10** Isotherm of the inspected PV module on August 29th, at 15:00

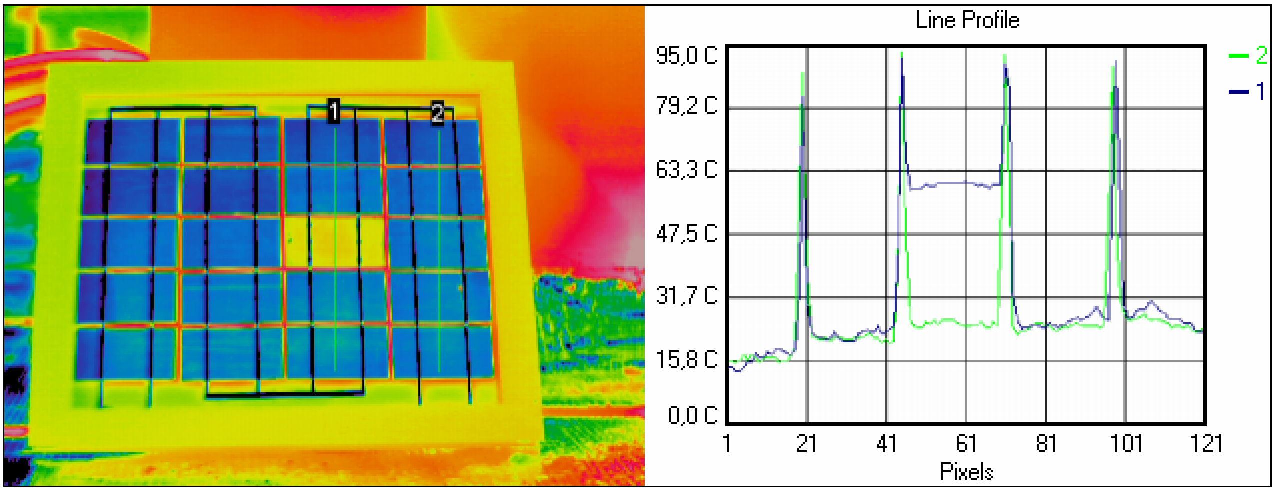


**Figure 11** Line profile analysis the inspected PV module on August 29th, at 15:00

## 5. Concluding Remarks

An experimental work has been realized to investigate the pertinent correlation among the operating temperature of a PV module in situ ($T_c$) measured using infrared thermography and its relative electrical performance. The performed measurements, among with the study of the thermodynamic model of a PV module, gave unambiguously promising results. The method indicated a possible problematic area of the employed non commercial photovoltaic module which was found and confirmed that it was related with an actual, unseen 2 mm crack.

In conclusion, infrared thermography appears to be a potential non-destructive method for the in situ evaluation of a PV module performance. The method gives fast, quite reliable and of easy interpretation results regarding to the condition of each solar cell in a PV module. Unfortunately, specific limitations referring to emissivity problems, the presence of glass in front of the solar cells and the undesirable dependency from the environmental (ambient and background) conditions have to be taken into account. In situ thermographic inspections to glass-coated commercial PV modules, as well as the use of active thermography for indoor or night measurements and the inspection of PV plants utilizing aerial thermography, are of further interest and investigation of the current research team which aspires to develop a complete PV module condition monitoring technique, with certain image processing and fault classification tools.

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