CHAPTER 5 THE IMPORTANCE OF CELL TEMPERATURE IN MODELLING THE ENERGY EFFICIENCY OF PV MODULES

Sebastien Jacques

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SÉBASTIEN JACQUES[1]

Abstract

This chapter deals with a simplified, meaningful thermal model to calculate photovoltaic (PV) cell temperature, which is of utmost importance in determining the electrical energy efficiency of PV modules. This model, which has been applied to standard PV modules (or Glass/Backsheet solar panels), takes into consideration ambient temperature, incident irradiance, and wind speed. A complete experimental database was built to calibrate this model. The results of the thermal modelling provide a heat transfer coefficient law, which may be implemented in a PV simulation tool. Two key elements of this approach can be highlighted. The results enable better calculation of the electrical energy production of PV modules and help to predict the energy efficiency of PV units.

Keywords: Cell temperature; thermal modelling; PV module; energy efficiency prediction.

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Introduction

Photovoltaic (PV) power plants currently offer ground-breaking solutions to the challenges of energy transition. PV systems may be designed in many configurations, including: standalone or grid-connected; fixed or tracking; and flat plate or concentrator operation [1]. At the moment, many simulation tools, market orientated and academic, such as PVsyst, can be used to define a baseline for sizing a PV unit [2], [3]. The main objective is to evaluate the technical performance of a PV unit through estimation of its annual energy yield, array yield, reference yield, and system losses [4].

The PV module is one of the key elements in sizing a PV power plant. In particular, it is of utmost importance to minimize the losses caused by its operating cell temperature (T_{cell}). The energy efficiency of the crystalline silicon cell technology used (i.e., monocrystalline or polycrystalline), which is one of the most popular silicon solar cell families, strongly depends on the T_{cell}-parameter. S. Chander et al. recently reported that the relative change in PV parameters with temperature can be found between –0.0025/°C and –0.0022/°C for open circuit voltage, and 0.002/°C, –0.0013/°C, and –0.002/°C for short circuit current, fill factor, and maximum output power, respectively [5].

The T_{cell}-parameter is not only dependent on total irradiance, but is also related to weather conditions to an extent that has yet to be fully assessed. In particular, the influence of ambient temperature, relative humidity, wind direction, and wind speed need to be more thoroughly studied [6]. Gaglia et al. have recently provided some initial responses. In particular, they have highlighted that PV temperature mainly depends on air temperature and solar irradiance, and less so on wind speed [7]. However, wind speed, which is often neglected because of a lack of detailed data, may especially have an impact on large scale PV systems (higher than 100 kWp) in so far as the modules are exposed to convective heat transfer on both sides [8].

This chapter discusses the relevance of a simplified thermal model used to analyse the influence of the T_{cell}-parameter on the energy efficiency of a PV module. The study is particularly focused on silicon cells assembled in a Glass/Backsheet solar panel. This kind of assembly is also known as a standard PV module. The results of cell temperature modelling may be input into PV simulation tools to better predict the overall performance, in terms of energy efficiency, of a PV power plant.

This chapter, which is a revised version of an article presented at the International Conference on Renewable Energies and Power Quality

(ICREPQ 2013), is divided into 3 sections [9]. The first one explains the methodology used in calculating the cell temperature through thermal modelling of a standard PV module. The second one describes the experimental procedure to calibrate the model. The final section discusses the relevance of such an approach with reference to the simulation results of 2 PV units (i.e., 2.6 kWp and 7.9 kWp). An in-house PV simulation tool based on the MATLAB development environment was used. The results are compared to those given by commercial software to highlight the robustness of this thermal model.

Simplified Modelling of Cell Temperature

Standard PV Module Thermal Modelling

Standard PV modules, also called Glass/Backsheet PV modules, are still widely used in contemporary solar applications [10], [11]. As can be seen in Figure 1, this kind of module is composed of several materials. A tempered sheet of glass is used at the front (with a thickness of between 2 to 4 mm). This material must have low reflective properties. Monocrystalline or polycrystalline PV cells are wired up in series and/or in parallel depending on the electrical ratings of the solar panel. EVA (ethylene vinyl acetate) is the polymer most often used to encapsulate these PV cells to ensure good insulation and durability. The EVA layer on top of the solar cell, must have excellent transmittance (higher than 90%). On the backside of the PV cells, a high transparency EVA layer (with a thickness of about 0.45 mm) is used. This kind of material allows a significant amount of sunlight to pass through. It also creates more aesthetically pleasing solar panels for mass-market applications, such as greenhouses and carports. A fluoropolymer backsheet is then used. The backing plate is generally composed of a Tedlar® PVF (polyvinyl fluoride) film (with a typical thickness of between 0,025 mm and 0,050 mm) because of its optimal balance of properties in terms of weather resilience, adhesion, and mechanical strength warranting a long PV module lifetime. All these materials are assembled within an aluminium supporting structure.

It is important to note that frameless double-glass PV modules have recently emerged, mainly to achieve a significant cost reduction [12]. This kind of solar panel is composed of a layer of glass, an encapsulating material at the topside of the PV cells, the solar cells, an encapsulating material at the backside of the PV cells, and another layer of glass. The methodology described in this chapter to model cell temperature can be adapted to this PV module technology.

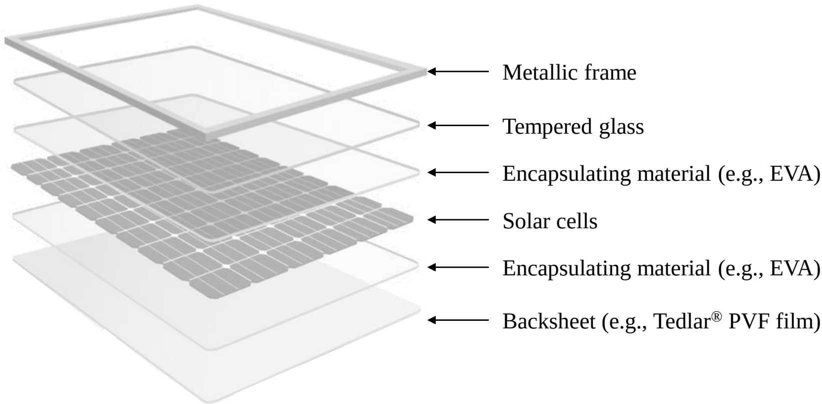

Figure 1. Cross-sectional view of a Glass/Backsheet PV module

A simplified approach for modelling the thermal behaviour of the Glass/Backsheet module (i.e., its cell temperature) in a steady-state is described here. It should be noted that the time to reach an equilibrium is not taken into consideration. In the case of transient modelling, the temperature behaviour must be simulated using several thermal resistance-thermal capacitance networks where each network corresponds to one material of the PV module assembly.

As can be seen in Figure 2, the thermal model of a Glass/Backsheet PV module is assumed to be symmetrical with the encapsulated solar cells [13]. Heat flow (Φ) is generated by thermal conduction. As a consequence, each material of the assembly has a conductive thermal resistance (R_{th}), which can be calculated from its physical properties (i.e., length [l] of the material through which heat must travel; area [S] of the surface conducting heat; thermal conductivity [k] of the material). The front side and back side of the solar panel are subjected to air-flow. Therefore, a convective thermal resistance (R_h) can be determined to complete the T_{cell}-parameter modelling. The R_h-parameter depends on the heat transfer coefficient (h), which is a key parameter to be determined. To sum up, as described in Equation (1), the cell temperature can readily be expressed as a function of: the ambient temperature (T_a); the conductive and convective thermal resistances (i.e., R_{th} and R_h); the area (A) of contact between the PV module and ambient air; and heat flow (Φ).

$$T_{cell} = T_a + \left(R_{th} + R_h\right) \cdot \Phi \tag{1}$$

$$R_{th} = \frac{l}{k \cdot S}; R_h = \frac{1}{h \cdot A}$$

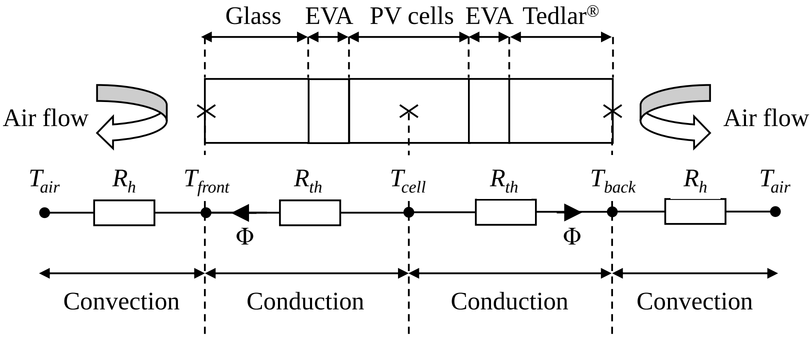

Figure 2. Simplified one-dimensional thermal modelling of a Glass/Backsheet PV module

Methodology to Calculate Cell Temperature

The calculation of the T_{cell}-parameter is based on the NOCT (nominal operating cell temperature) coefficient. This value is often used by PV module manufacturers to compare the performance of various solar panel designs in the same conditions (i.e., incident solar radiation of 800 W/m^2; ambient temperature of 20 °C; wind speed of 1 m/s on both front and back surfaces of the solar panel; tilt angle of the PV module of 45°) [14], [15].

Equation (2) gives the heat balance in open-circuit conditions for both the NOCT and operating conditions. From Equation (1) and Equation (2), it is now possible to write the heat balance according to the thermal modelling of the PV module (see Equation (3)). In this equation, the cell temperature depends particularly on the heat transfer coefficient (*h*). This parameter can be determined as a function of real conditions i.e., such as the wind speed (*w*). It is a matter of both experimentally extracting the *h*(*w*) relationship and comparing the values with the ones in the literature.

$$T_{cell} = T_a + \left(\frac{NOCT - 20}{800}\right) \cdot G_{inc} \tag{2}$$

where G_{inc} is the in-plane tilted irradiance.

$$T_{cell} = T_a + \left(\frac{NOCT - 20}{800} \right) \cdot G_{inc} \cdot \frac{R_{th} + R_{h(w)}}{R_{th} + R_{h_{NOCT}}} \quad (3)$$

where: R_{th} is the thermal resistance of the solar panel in conduction mode; $R_{h(w)}$ and R_{hNOCT} are the convective thermal resistances of the PV module depending on the wind speed and under the NOCT conditions, respectively

Model Validation using an Experimental Calibration

Experimental Environment

Figure 3 shows the experimental environment. A monocrystalline PV module (Schüco MPE 175 MS 05) with a rated peak power of 175 Wp was used for the measurements. A data acquisition system (Expert Key 100L, Delphin Technology) was optimally networked by Ethernet. Many reference temperatures were monitored and stored using the ProfiSignal software tool. Several T-type thermocouples were used. 6 thermocouples were fixed on the front and back sides of the PV module. Two other thermocouples were placed in direct contact with the PV cells to measure the T_{cell}-parameter. Finally, 2 thermocouples were used to measure the ambient temperature. A pyranometer (with its tilt angle equal to 35°) was directly mounted on the solar panel. This equipment was used to measure the global incident solar radiation on the surface of the PV module. It is important to note that this pyranometer was previously calibrated with a standard pyranometer in line with the measurements specified by the manufacturer (7 μV/(kW.m^2)). The relative wind speed was measured using an anemometer (rotary magnet), which was fitted with a wind vane to check the wind direction. A reed switch was arranged in the plane of the magnet. Its role was to emit an electrical pulse every time the magnet passed over. The signals (frequency and voltage proportional to the rotation angle) from the wind vane were analysed by the data acquisition system. A wind tunnel was used to set a constant wind speed (the maximum speed value was equal to 40 km/h). An airy screen was also set up to protect the PV module against moderate breezes. It is important to note that all the real experimental tests were done on sunny days with a particular focus on the evolution of the ambient temperature. Indeed, this had to be as stable as possible so as not to interfere with data acquisition.

From the equations previously described, the *h*-parameter can be deduced from the measurements.

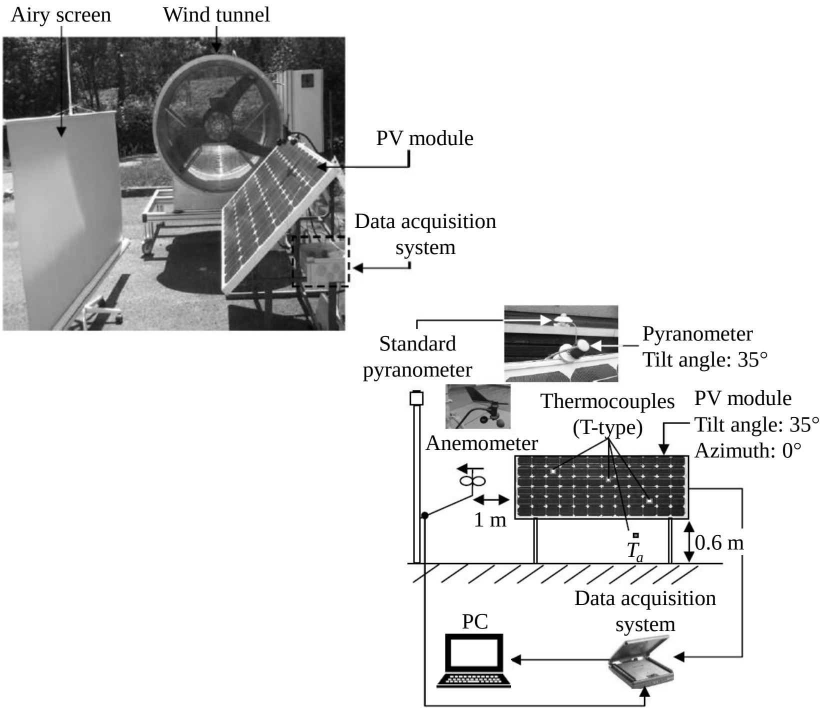

Figure 3. Experimental environment

Extraction of the Heat Transfer Coefficient

A number of sets of measurements were performed over many weeks thanks to favourable weather conditions (i.e., incident solar radiation of 800 W/m^2; ambient temperature higher than 20 °C; negligible breezes). The speed of the wind tunnel was adjusted from 1 km/h to 30 km/h.

Fig. 4 shows the evolution of the *h*-parameter as a function of wind speed. The results highlight a linear change. The confidence boundaries are visible on the graph. In particular, the median value of the h_{NOCT}-parameter at 3.6 km/h, i.e. under the NOCT conditions (wind speed of 1 m/s), is about 16.7 W/(m^2.K). This value is close to what can be found in the literature (between 15 W/(m^2.K) and 20 W/(m^2.K)) [16], [17].

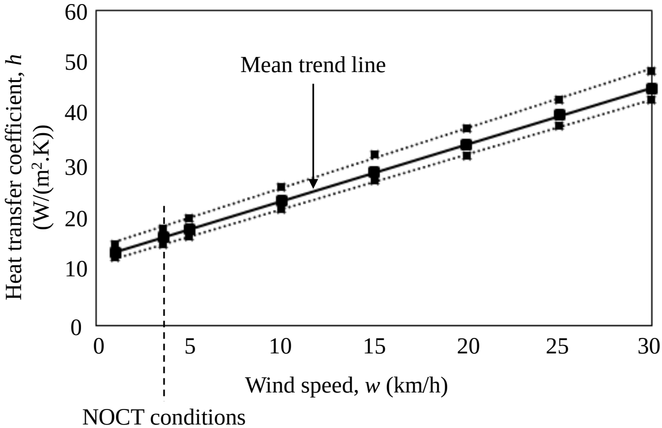

Figure 4. Heat transfer coefficient evolution in relation to wind speed

Main Results and Discussion

Model Implementation in a PV Software Tool

The previous results of the thermal modelling were directly implemented in the PVLab software tool. This tool has been developed recently to offer users a highly flexible PV simulator [2]. As can be seen in Figure 5, PVLab, which is based on the MATLAB development environment, allows users to personalize various models (i.e., optical, electrical, and thermal) and databases (i.e., the PV components such as inverters, solar panels, and, above all, meteorological databases). Therefore, many parameters can be changed—this is especially relevant for wind speed. It undeniably has added value, because existing marketed or free PV simulators cannot provide such capabilities (those simulation tools are most often distributed in the form of executable programs). To sum up, the main purpose of the PVLab simulator is to gain a better understanding of the impact of the various models and databases both on the production of electrical energy and the efficiency of PV power plants.

Hay's equations are used to calculate the global and diffuse solar irradiance on tilted planes like solar panels [18].

The electrical modelling of a PV module (see Fig. 6 and Equation (4)) is commonly described as a single-diode equivalent circuit including the influence of the serial and shunt resistances [19].

For the thermal modelling, the evolution of the *h*-parameter in relation to wind speed (see Figure 4) was used as a key input for the simulator. This is a big improvement on commercial or free PV simulators, such as PVsyst. The latter, in particular, uses the global heat balance approach to calculate cell temperature. Such an approach considers the heat transfer coefficient to be constant. As such, the NOCT method described in this chapter allows for a more thorough analysis of the energy efficiency of PV modules.

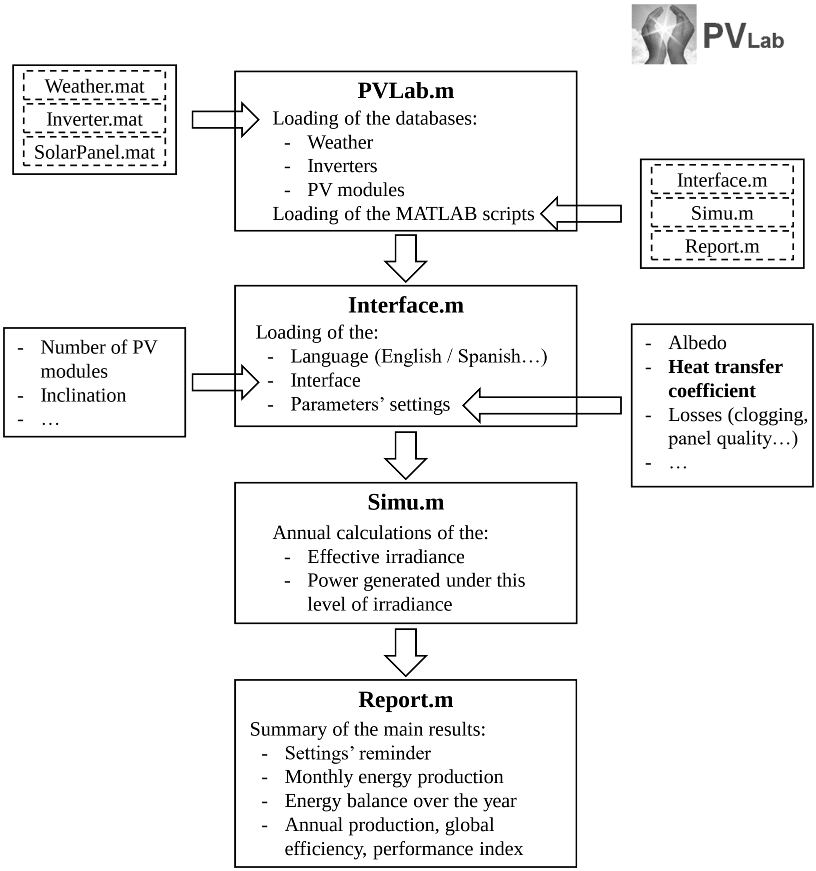

Figure 5. Global architecture of the PVLab simulation tool

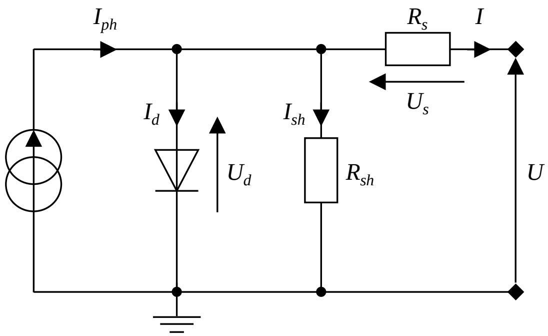

Figure 6. Single-diode equivalent circuit modelling

$$I = N_p I_{ph} - N_p I_0 \cdot \left(e^{\frac{\alpha}{N_s} \cdot \left(U + \frac{N_s}{N_p} R_s I \right)} - 1 \right) - \frac{U + \frac{N_s}{N_p} R_s I}{\frac{N_s}{N_p} R_{sh}} \tag{4}$$

where: N_p and N_s are the number of PV cells connected in parallel and in series, respectively; I_{ph} is the photocurrent; I_0 is the saturation current; α is the absorption coefficient

Case Studies, Main Results, and Discussion

The yearly electrical energy production of 2 medium PV plant configurations (i.e., 2.6 kWp and 7.9 kWp) was computed using PVLab. First of all, the results produced by PVLab were compared with those produced by PVsyst, using the same input data. The aim was to confirm the utility of PVLab. The influence of wind speed on solar energy production for one PV unit (i.e., 2.6 kWp) and using PVLab, is discussed.

For the simulation settings, the meteorological data (from the Meteonorm database), recorded in Tours (47°23’38” N; 0°41’48” E), France, were used. Polycrystalline PV modules (Solar World SW220; peak rated power of 220 Wp) were used. The tilt angle of each solar panel was equal to 30°. Each grid-connected system used an inverter: the SMA Sunny Boy SB3300 (nominal AC output of 3.3 kW), and the SMA Sunny Mini Central 9000TL (nominal AC output of 9 kW), for the 2.6 kWp and 7.9 kWp PV installations, respectively. It is important to note that PVLab and PVsyst were run using the same mechanical and electrical databases to characterize the PV modules and inverters.

Table I summarizes the simulation results for the first case study (i.e., the comparison between PVLab and PVsyst). The data show that the 2 PV simulation tools give approximately the same results (with a relative difference of about 1%), whatever the nominal power of the medium PV plant. For instance, for the PV unit with a nominal power of 2.6 kWp, the values of the yearly electrical energy production predicted by PVLab and PVsyst equalled 3,202 kWh and 3,239 kWh, respectively. All these simulation results confirm the relevance of PVLab in comparison to PVsyst, which is still a top simulator in the photovoltaic sector.

Table I: Simulation results for the first case study. Comparison between PVLab and PVsyst

Nominal power (kWp) of the PV unit	Yearly electrical energy production (kWh) predicted by PVLab	Yearly electrical energy production (kWh) predicted by PVsyst	Relative difference (%)– PVLab vs. PVsyst
2.6	3,202	3,239	– 1.1
7.9	9,516	9,658	– 1.2

In the preceding data, the wind speed (i.e., 1 m/s) was constant as described in the standard operating conditions [15]. This value is fixed in the PVsyst software tool without the ability to change it. As such, when using PVsyst it is not possible to study the influence of wind speed on the energy efficiency of PV modules. The versatility of the PVLab simulator was intended to provide partial answers to resolve this issue.

In a second case study, the influence of wind speed was taken into consideration through analysis of the *h*-parameter, as described in the previous sections. The study was performed on the PV unit with a nominal power of 2.6 kWp. Table II sums up the main results. The yearly electrical energy production predicted by PVLab slightly increases when the wind speed increases. For example, this increase is about 4% when the wind velocity rises from 1 m/s to 10 m/s. Even if those results confirm that wind speed is not the primary factor in electrical energy production, this parameter might have a greater impact on large scale PV plants.

Table II: Simulation results for the second case study. Impact of wind speed on the yearly electricity production of a PV unit (2.6 kWp)

Wind speed (m/s)	Yearly electrical energy production (kWh) predicted by PVLab	Relative difference (%) vs. wind speed of 1 m/s
1.0	3,202	0.0
2.0	3,250	+ 1.5
5.0	3,298	+ 3.0
10.0	3,330	+ 4.0
15.0	3,346	+ 4.5

Conclusions

This chapter has highlighted the relevance of a simplified thermal model for a PV module to calculate its cell temperature from irradiance, ambient temperature, and wind speed. This thermal model has been applied to Glass/Backsheet solar panels, which are still widely used in modern PV units. Several measurements in real operating conditions were performed to calibrate the model.

The results of the experimental procedure show that the heat transfer coefficient increases linearly with wind speed. More specifically, these results include the value specified in the standard operating conditions (i.e., between 15 W/(m^2.K) and 20 W/(m^2.K)) at a wind speed of 1 m/s. Most importantly, the heat transfer coefficient is not constant, unlike that which is currently implemented in commercial or free PV software tools, such as PVsyst.

All these results were input into an in-house PV simulation tool, named PVLab, which is based on the MATLAB development environment. PVLab is a powerful, adaptable PV simulator that allows the user to modify its internal models (i.e., optical, electrical, and thermal models) and databases (i.e., meteorological data, and PV components such as PV modules and inverters).

Two case studies were simulated using PVLab and PVsyst.

The first one consisted of estimating the yearly electrical energy production of 2 medium PV plant configurations (i.e., 2.6 kWp and 7.9 kWp). In the same configurations, PVLab and PVsyst give approximately the same results. As such, the utility of PVLab as a simulator has been proven.

The second one consisted in obtaining a better understanding of the influence of wind speed on the yearly electrical energy production of a medium PV unit (i.e., 2.6 kWp). PVLab had to be used here because PVsyst does not offer the possibility of changing this parameter. The simulation results showed that the yearly electrical energy production predicted by PVLab does not increase significantly when the wind speed increases. Even if those results confirmed that wind speed is not the primary factor in electrical energy production, this parameter might be of significant interest in large scale PV plants.

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