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PV Cell Temperature/ PV Power Output Relationships Homer Methodology Calculation

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***Abstract*— Because of the intermittent solar irradiation which highly influences the resulting energy production, the major aspects in the design of PV power generation systems are the reliable power supply of the consumer under varying atmospheric conditions and the corresponding total system cost.**

Thus it is necessary to select the number of PV modules and batteries, and their installation details such as the power will be uninterruptedly supplied to the electrical load, and simultaneously the minimum system cost would be achieved [1]. But it's especially so judicious to take into account the whole system parameters such as cell temperature, a task ensured by several software tools as Homer from the NREL lLaboratory [2].

As known, meteorological parameters especially the array temperature, do not remain constant the whole day long, but change considerably. Then, it is worth investigating the influence of the daily average temperature variation on the predicted performances of the optimized system.

It's so important to seize how such software proceeds to get around any result calculation and a possible problem at the same time.

So, the goal achieved through this study is to investigate the influence of the cell temperature and head changing effects on the system performances. So an approach by a mathematical formalism is then indispensable.

***Keywords*- solar layer; PV cell temperature; PV power output; mathematical formulation; calculation; Homer**

I. INTRODUCTION

Recently, awareness of the importance of protecting the global environment has been growing, leading to calls for progress in the effective use of energy in various fields. As a result, not only methods for saving energy but the development of the new energy sources also has been investigated. PV cells are currently considered to be a new energy source, and a great deal of research has been conducted in this field over the last few decades. As a result, the major disadvantages previously associated with the application of PV power generation, such as initial cost, generation efficiency, and reliability; no longer present such a significant problem. PV generation is a flexible power generation method that is applicable in both small and large power generation plants, i.e. plants that generate anywhere from less than 3 kV to over 100 kVA.

Solar energy is the most important energy resource to human being since it is clean, pollution-free, and inexhaustible. Due to the rapid growth in the semiconductor and power electronics techniques, the photovoltaic energy gains great potential in the applications of solar energy.

II. CALCULATION METHODOLOGY

A. PV Cell Temperature

The PV cell temperature is the temperature of the PV array surface. By night it is the same as the ambient temperature, but in full sun the cell temperature can exceed the ambient temperature with 30 °C or up.

If, in the PV Array inputs window we may choose to consider the effect of temperature on the PV array, then HOMER will calculate the cell temperature in each time step, and use that to calculate the power output of the PV array. This article describes how HOMER calculates the cell temperature from the ambient temperature and the radiation striking the array.

We start by defining an energy balance for the PV array, using the following equation from Duffie and Beckman (1991):

$$\tau\alpha G_T = \eta_c G_T + U_L\left(T_c - T_a\right) \qquad (1)$$

Where:

τ Solar transmittance of any cover over the PV array (%).

α Solar absorptance of the PV array (%)

G_T Solar radiation striking the PV array (kW/m2).

η_c : the electrical conversion efficiency of the PV array (%)

U_L Coefficient of heat transfer to the surroundings ($kW/m^2{}^\circ C$).

T_c PV cell temperature (°C).

T_a Ambient temperature (°C).

The equation above states that a balance exists between, by one hand, the solar energy absorbed by the PV array, and by the another hand, the electrical output plus the heat transfer to the surroundings. We can solve that equation for cell temperature to yield:

$$T_c = T_a + G_T \left(\frac{\tau\alpha}{U_L} \right) \left(1 - \frac{\eta_c}{\tau\alpha} \right) \tag{2}$$

It is difficult to measure the value of $\left(\tau\alpha / U_L \right)$ directly, so instead manufacturers report the Nominal Operating Cell Temperature (NOCT), which is defined as the cell temperature that results at an incident radiation of 0.8 kW/m2, an ambient temperature of 20 °C, and no load operation (meaning $\eta_c = 0$). We can substitute these values into the above equation and solve it for $\tau\alpha / U_L$ to yield the following equation:

$$\frac{\tau\alpha}{U_L} = \frac{T_{c,NOCT} - T_{a,NOCT}}{G_{T,NOCT}} \tag{3}$$

Where:

$T_{c,NOCT}$ Nominal operating cell temperature (°C).

$T_{a,NOCT}$ Ambient temperature at which the NOCT is defined (20 °C).

$G_{T,NOCT}$ Solar radiation at which the NOCT is defined (0.8 kW/m2).

- *Nominal operating cell temperature*

The nominal operating cell temperature is the surface temperature that the PV array would reach if it were exposed to 0.8 kW/m2 of solar radiation, an ambient temperature of 20 °C, and a wind speed of 1 m/s. Sometimes called the "normal operating cell temperature" and frequently abbreviated NOCT, the nominal operating cell temperature provides a measure of how the PV cell temperature (the surface temperature of the PV array) varies with the ambient temperature and the solar radiation. HOMER uses the NOCT to calculate the PV cell temperature.

PV manufacturers typically report the nominal operating cell temperature as part of their product data. In our non-exhaustive survey of commercially-available PV modules in November 2007, about 60% percent of the product data sheets specified the NOCT, with the values varying over a narrow range from 45 °C to 48 °C.

If we assume that $\tau\alpha / U_L$ is constant, then we can substitute this equation into the cell temperature equation to yield:

$$T_c = T_a + G_T \left(\frac{T_{C,NOCT} - T_{a,NOCT}}{G_{T,NOCT}} \right) \left(1 - \frac{\eta_c}{\tau\alpha} \right) \tag{4}$$

HOMER assumes a value of 0.9 for $\alpha\tau$ in the equation above, as Duffie and Beckman (1991) suggest. Since the term $\eta_c / \tau\alpha$ is small compared to unity, this assumption does not introduce significant error.

B. PV Array Power Output

HOMER assumes that the PV array always operates at its maximum power point (or at its top power), as it would if it were controlled by a maximum power point tracker. That means HOMER assumes the cell efficiency is always equal to the maximum power point efficiency:

$$\eta_c = \eta_{mp} \tag{5}$$

Where:

η_{mp} Efficiency of the PV array at its maximum power point (%).

So in the equation for cell temperature we can replace η_c with η_{mp} to yield:

$$T_c = T_a + \left(T_{C,NOCT} - T_{a,NOCT} \right) \left(\frac{G_T}{G_{T,NOCT}} \right) \left(1 - \frac{\eta_{mp}}{\tau\alpha} \right) \tag{6}$$

But η_{mp} depends on the cell temperature T_c . HOMER assumes that the efficiency varies linearly with temperature according to the following equation:

$$\eta_{mp} = \eta_{mp,STC} \left[1 + \alpha_p \left(T_c - T_{c,STC} \right) \right] \tag{7}$$

$\eta_{mp,STC}$ is the maximum power point efficiency under standard test conditions (%);

PV manufacturers rarely report this efficiency in their product brochures, but we can calculate it for any PV module by using the following equation:

$$\eta_{mp,STC} = Y_{PV} \,/\, A_{PV} \; G_{T,\,STC} \qquad (8)$$

Where:

- Y_{PV} Rated power output of the PV module under standard test conditions (kW).
- A_{PV} Surface area of the PV module (m2).
- $G_{T,\,STC}$ Radiation at standard test conditions (1 (kW/m2).
- $T_{c,STC}$ Cell temperature under standard test conditions (25 °C).
- α_p Temperature coefficient of power (%/°C).

o The temperature coefficient of power α_p indicates how strongly the PV array power output depends on the cell temperature, meaning the surface temperature of the PV array. It is a negative value once power output decreases with the increase of cell temperature. PV modules manufacturers usually provide this coefficient in their product brochures, often labelled either as "temperature coefficient of power", "power temperature coefficient", or "max. power temperature coefficient".

If the product brochure does not specify the value of the temperature coefficient of the power, it may contain a chart showing the normalized performance versus cell temperature, like the sample shown below. In such a graph, the slope of the power line (labelled Pmax in this sample) represents the temperature coefficient of the power. The normalized open-circuit voltage and short-circuit current also appear in this sample.

Some product brochures do not specify the temperature coefficient of power, but do specify the temperature coefficient of the open-circuit voltage. In that case, you can calculate the temperature coefficient of the power using the approximation suggested by Duffie and Beckman (1991):

$$\alpha_p \approx \frac{\mu_{Voc}}{V_{mp}} \qquad (9)$$

Where:

μ_{Voc} Temperature coefficient of the open- circuit voltage (V/°C)

V_{mp} Voltage at the maximum power point under standard test conditions (V).

The temperature coefficient of the power is normally negative, meaning that the efficiency of the PV array decreases with increasing cell temperature.

We can substitute η_{mp} efficiency equation into the preceding cell temperature equation and solve for cell temperature to yield:

$$T_c = \frac{T_a + \left(T_{c,NOCT} - T_{a,NOCT}\right)\left(\frac{G_T}{G_{T,NOCT}}\right)\left[1 - \frac{\eta_{mpSTC}\left(1 - \alpha_p T_{c,STC}\right)}{\tau\alpha}\right]}{1 + \left(T_{c,NOCT} - T_{a,NOCT}\right)\left(\frac{G_T}{G_{T,NOCT}}\right)\left(\frac{\alpha_p \eta_{mpSTC}}{\tau\alpha}\right)} \qquad (10)$$

The implicit and explicit correlations for the PV operating temperature may be found in [3].

It's to notice that:

- The temperatures in the above equation must be in Kelvin. HOMER uses this equation to calculate the cell temperature in each time step.
- PV manufacturers rate the power output of their PV modules at standard test conditions (STC), meaning a radiation of 1 kW/m2, a cell temperature of 25 °C, without wind. Standard test conditions do not reflect typical operating conditions, since full-sun cell temperatures tend to be much higher than 25°C.

HOMER uses the following equation to calculate the output of the PV array:

$$P_{PV} = Y_{PV} \; f_{PV} \left(\frac{\overline{G}_T}{\overline{G}_{T,STC}}\right)\left[1 + \alpha\left(T_c - T_{c,STC}\right)\right] \qquad (11)$$

Where: f_{PV} is the PV derating factor (%).

o The PV derating factor is a scaling factor that HOMER applies to the PV array power output to account for reduced output in real-world operating conditions compared to the conditions under which the PV panel was rated.

The derating factor is used to account for such factors as soiling of the panels, wiring losses, shading, snow cover, aging, and so on. If you choose not to explicitly model the effect of temperature on the PV array, then you should also include temperature-related effects in the derating factor.

If the effect of temperature on the PV array is not modelled, HOMER assumes that the temperature coefficient of power is zero, so that the above equation simplifies to:

$$P_{PV} = Y_{PV} \; f_{PV} \left(\frac{\overline{G}_T}{\overline{G}_{T,STC}} \right) \qquad (12)$$

II. APPLICATION ON A REMOTE REGION, CASE OF STUDY: TINDUF PREFECTURE

It's intended to meet needs of a peak power of 5.5 kW and energy of 26 kWh/d of a small village in Tindouf prefecture.

A. Geographical data

Location of the studied site is given in Fig. 1;
Tindouf geographical data are given in Table 1;

B. Meteorological data

1) Data related to irradiance:

Once calculated on horizontal area, daily solar irradiation varies from 3.29 kWh/m2/d in December to 7.99 kWh/m2/d in July with an annual average of 5.88 kWh/m2/d.

On a 26°-inclined area this radiation varies between 5.23 kWh/m2/d in December and 7.11 kWh/m2/d in April, the annual average is 6.4 kWh/m2/d.
Daily irradiance variation (change) during seasons. It is given in Fig. 2;
The daily radiation is as illustrated on Fig. 3;

2) Data related to ambient temperature:

The monthly maximal average temperature is 33.3 °C in July when the minimal average temperature is 10.3 °C in January, which makes an annual average of 22.9 °C.

The annual ambient temperature is given in Fig. 4;

The monthly ambient temperature profile is represented by Fig. 5;
The daily ambient temperature profile is illustrated in Fig. 6;

3) Data related to load:

AC primary load daily profile along the diveres seasons is represented in Fig. 7;

III. RESULTS

The system architecture is as given in Fig. 8;

A. SEH configurations (depending on the present net cost)

The configuration of this hybrid system is as shown below in the Tables 2 and 3;

B. Main results

Main results are gives in Table 4;
The incident solar is represented in Fig. 9;
In the Fig. 10, incident solar is superposed to the PV power;
Incident solar vs. PV power is illustrated in Fig. 11;
Monthly average electric production is shown in Fig. 12;
It's DMap is represented in Fig. 13;
Is represented in Fig. 14 the hourly evolution a year long of load and PV production;

Fig. 14 clearly shows that the PV production covers fully and at all times the energy demand, which is what have confirmed us the Figs. 15 a) and b), which give respectively the distribution of monthly averages of these characteristics;

Fig. 16 represents the hourly evolution of the photovoltaic power, the state of charge of the battery as well as the profile of the load, for two typical days on January 17 and August 16.

The pproduction of PV field is between about 6:30 am and 06:30 pm for the day of January 17, and between about 6:30 am and 07:30 pm for the day of August 16. These times correspond to the times of sunrise and sunset from the site. The PV array is able to meet the load and charge the batteries that take over during the night.

Fig. 17 represents the time evolution in three days of June along of the PV output and input power of the battery, with a zoom of the first day;

Through this figure we may see that the battery is charged during the photovoltaic production period, taking place between 6.30 am and 06.30 pm, in the illustration of June 13, the power of the battery is positive throughout this period. The rest of the day the battery discharges, and it covers the demand, its power in this case is negative. Discharge and recharge of the battery are imposed by the consumer and production systems.
We give in Fig. 18, the annual hourly evolution of energy demand and excess electricity;

We note that the excess energy (estimated at 3,084 kWh/y) is indeed in the intervals with low energy demand. The largest surpluses were recorded in March and April, the lowest take place in November and December.

For further details, we represent in Fig. 19 the excess electrical production monthly average;

And in Fig. 20 is given the excess electrical production daily profile during seasons;
A superposition of AC primary load, PV power and electricity excess is illustrated in Fig. 21;
We give in Fig. 22 the yearly hourly evolution of the temperature of the cells, with a zoom on the period from August to Septembe.

In the Figs. 23 and 24, are represented respectively the distribution of average monthly temperatures of the cells and their map data (DMap);

The average monthly temperatures of cells increase from the average of 15 ° C in January, reaching an average of 40 ° C in the summer time when it stabilizes around, then decreases until to reach 22 ° C in November and finally 16 ° C in December. The annual average is 29 °C. DMap illustrates this distribution in color.
Their reference temperature follows the same logic evolution than the peaks; this is seen quite clearly on the daily temperature profile of these cells, during each month of the year, given in Fig. 25;

This reference temperature therefore varies during the month, but also the same day, corresponding to the hours of sunrise and sunset. It is located at around 10 °C one day of

January, equaling 33 °C in one day of August through 23 °C in April.
An example of these changes is shown in Fig. 26 which represents the cells temperatures corresponding to four days in two different months, April and May;

Why are these fluctuations?

We try, in the same context to elucidate graphically existing link between global radiation, PV production and cell temperature, features that are represented by the Fig. 27;

It is clear, from the Fig. 27 that the temperature of the PV cells at any time follows the evolution of global solar radiation. PV production, which correlates with the incident radiation changes inversely with cells temperature, to the peaks in the temperature graph correspond in fact hollows of the PV power produced. This is because the efficiency of a solar cell, in addition to irradiance, also depends greatly on the temperature. The mechanism can be summarized to the following: Exposed to solar radiation, it is likely to heat up. In addition, some of the radiation absorbed is not converted into electrical energy but dissipated as heat. Therefore, the temperature of a cell is always higher than the ambient temperature, where the Normal Operating Conditions Temperature NOCT convention.

The cell temperature has a great influence on its electrical performances. The lower the temperature, the more effective it is.
Previous studies have demonstrated that each degree of warming causes a yield loss of about 0.5%. Empirically, the photocurrent increases slightly with the temperature, a range of 0.05 %/°K for a silicon cell (1.1 eV). This same cell loses 0.45 %/°C of its power, another made of Gallium Arsenic (GaAs) (1.4 eV) loses about 0.21 %/°C [5].

The maximum power point may in the same way fluctuate significantly.
Development programs of solar cells operating at high temperatures are underway, including those enrolling in future NASA missions.
The hourly evolution battery SOC is shown in Fig. 28;
In Fig. 29 is shown the distribution of battery SOC monthly averages;
The battery SOC daily profile during seasons is given in Fig. 30;

According to these figures reflecting the state of charge of the batteries for the rest of the year, we find that these undergo deep discharge averaging about 70% during the winter period, and other more moderate during the rest of the year. Hourly powers to the input and to the output of the inverter are superposed in Fig. 31;

The output power of the inverter maintains the same wavelength as its entrance, but diminished in quantity due to losses in the same inverter form.

There once again is highlighted the interest of the inclination of the PV panels via the simple evaluation in terms of PV array power output, represented in Fig. 32;

Indeed, the production is estimated at 15.320 MWh/y in the non-tilted system, as it reaches 18.443 MWh/y in the tilted system, so 3.123 MWh/y more.
With a 9 kWp PV field, 24 batteries of 7.6 kWh each and a 5 kW inverter, respectively versus 9.5 kWp, 12 * 7.6 kWh and 5 kW, the impact on the economic characteristics is striking that just sums up the cost of energy.
The price of energy is estimated at 0.3 USD/kWh in the not tilted PV system, and
0.18 USD/kWh in the inclined one.

IV. CONCLUSION

A key variable for the photovoltaic conversion process is the operating temperature of the cell/module.

Regarding to the relevant weather variables, and qualitatively speaking, it was found that the PV cell temperature rises over the ambient one and is extremely sensitive to wind speed, less so to wind direction, and practically insensitive to the atmospheric temperature [4]. On the other hand, it depends obviously and strongly on the impinging irradiation, i.e. the solar radiation flux on the cell or module.

But we have to be careful when applying a particular expression for the operating temperature of a PV module because the available equations have been developed with a specific mounting geometry or building integration level in mind.

Therefore, the reader of this paper is urged to consult the original sources when seeking a correlation suitable for a particular application.

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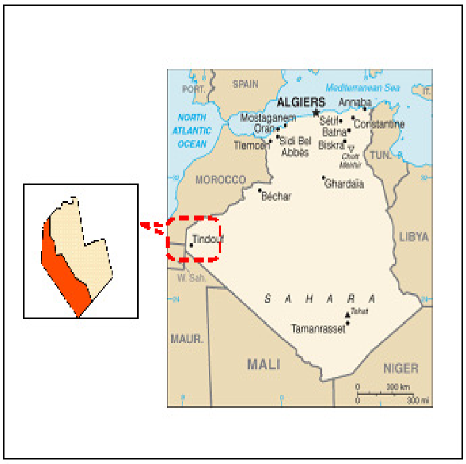


Fig. 1 Location of the studied site

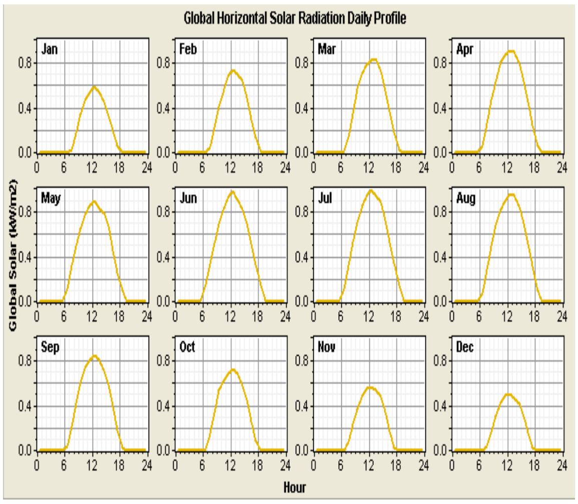


Fig. 2 Daily irradiance profile during seasons

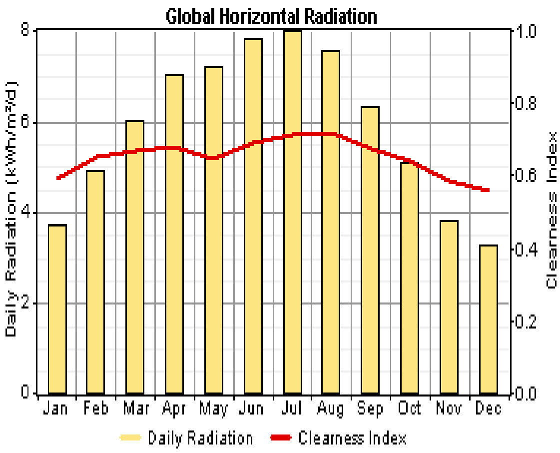


Fig. 3 Daily global horizontal irradiation

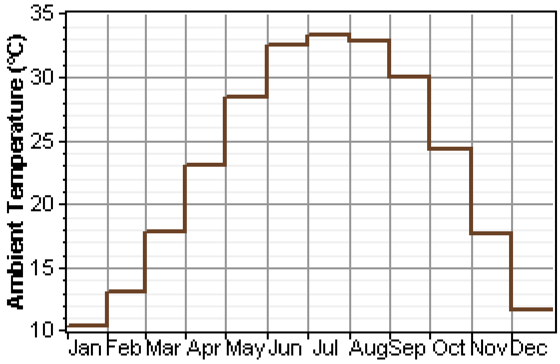


Fig. 4 Profile of the annual ambient temperature

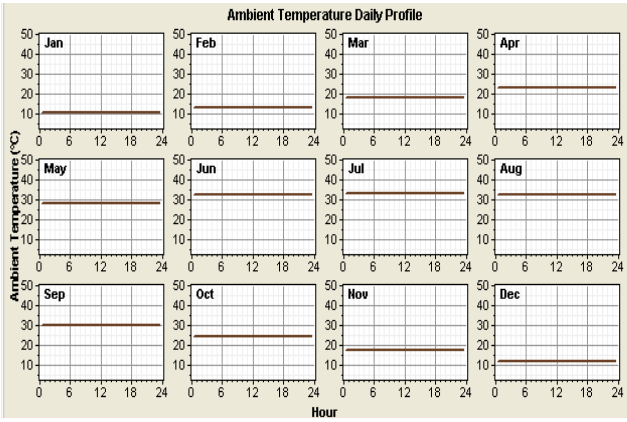


Fig. 5 Monthly average ambient temperature

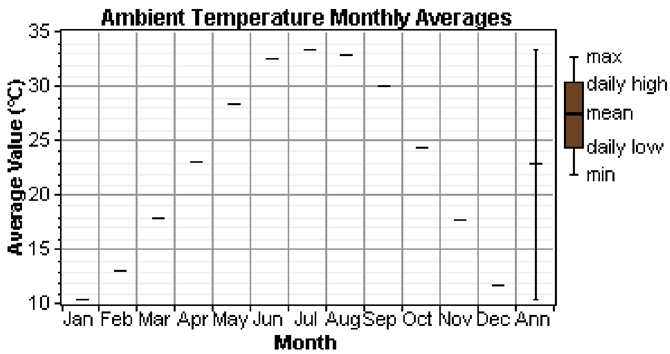


Fig. 6 Daily ambient temperature profile

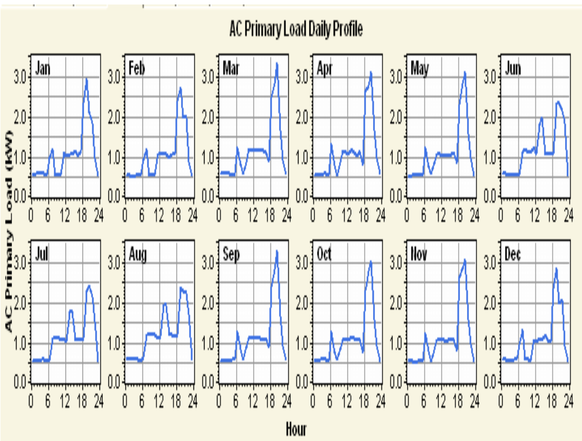


Fig. 7 AC primary load daily profile

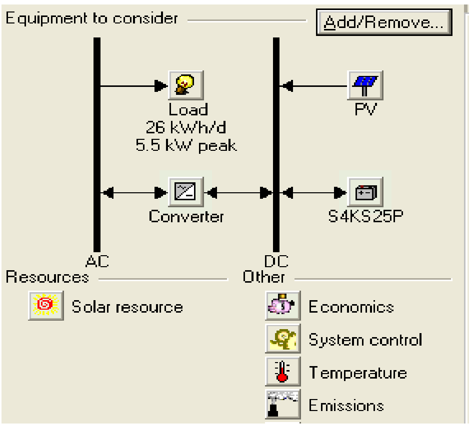


Fig. 8 System architecture

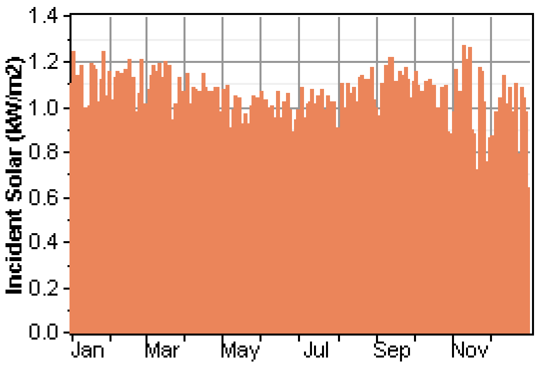


Fig. 9 Incident solar

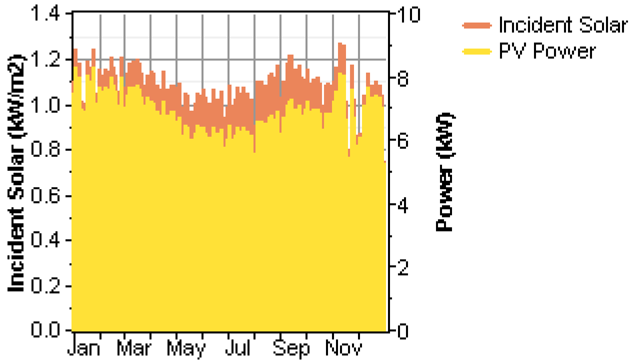


Fig. 10 Incident solar superposed to the PV power

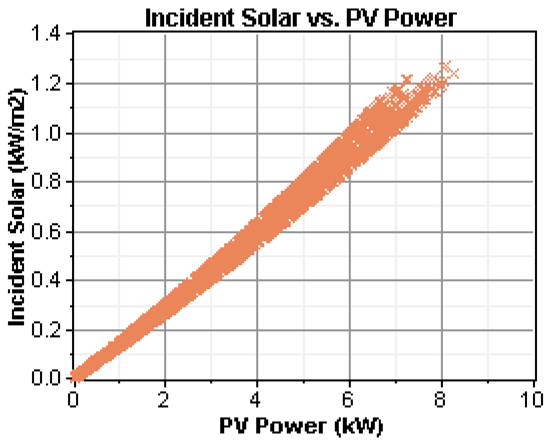


Fig. 11 Incident solar vs. PV power

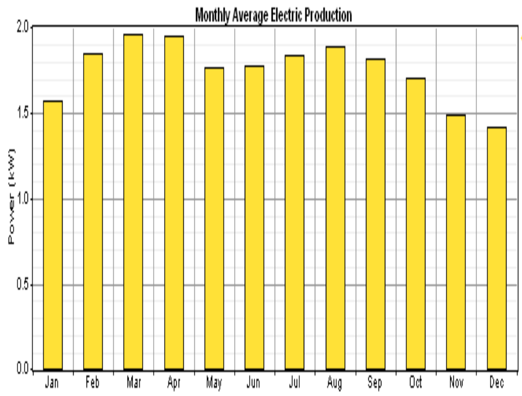


Fig. 12 Monthly average electric production

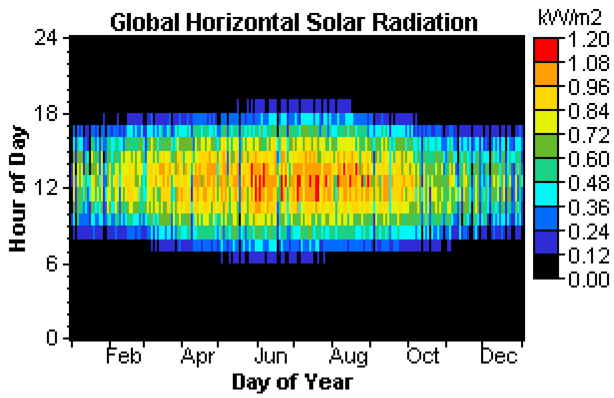


Fig. 13 DMap of the PV output

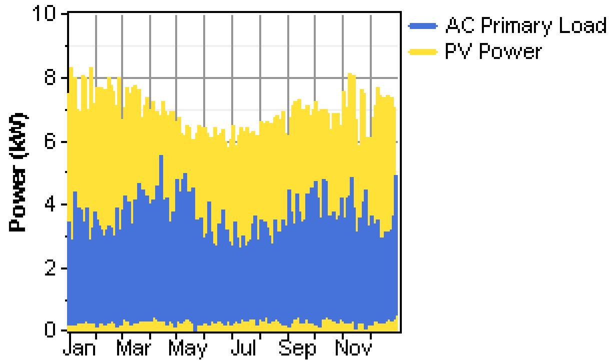
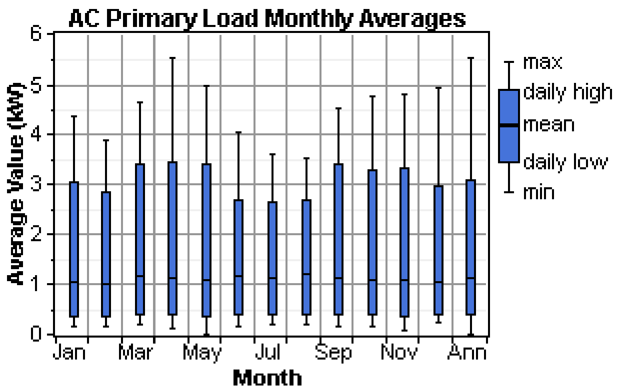
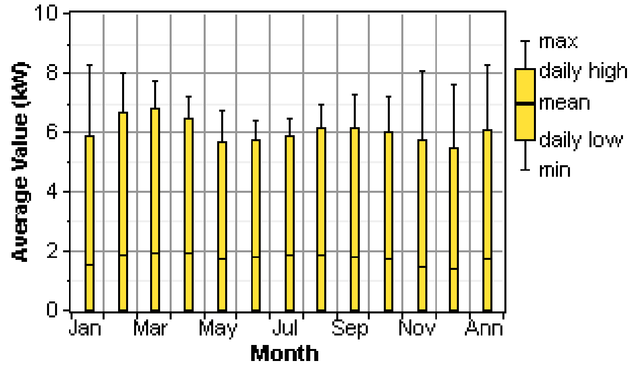


Fig. 14 Superposition of AC primary load and PV power



a)



b)

Fig. 15 Distribution of the monthly average load and producted powers

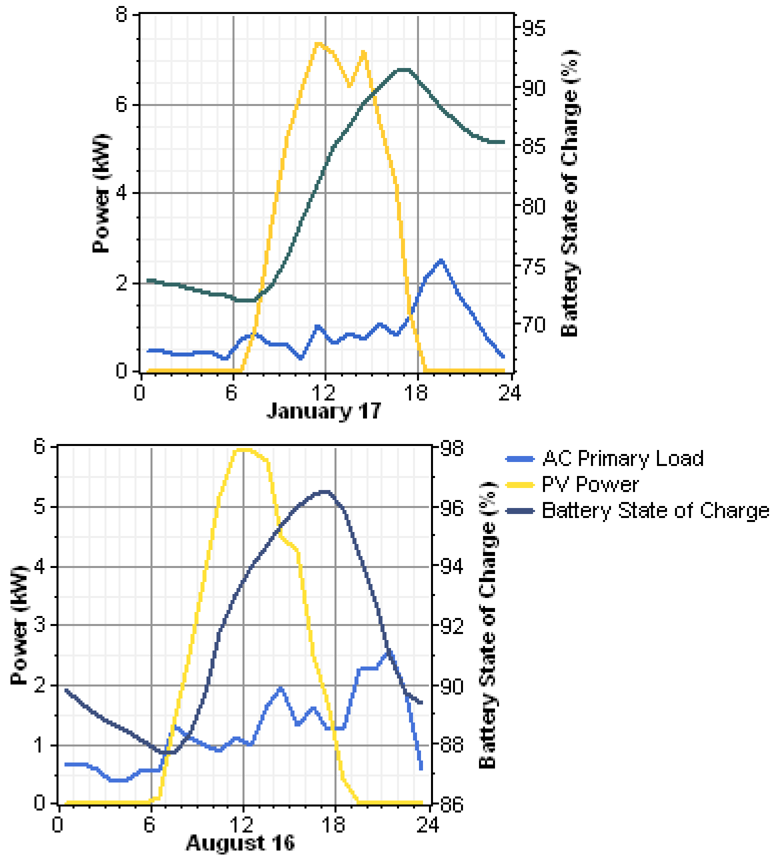


Fig. 16 Hourly evolution of load, PV power and SOC, for two typical days (January 17 and August 16)

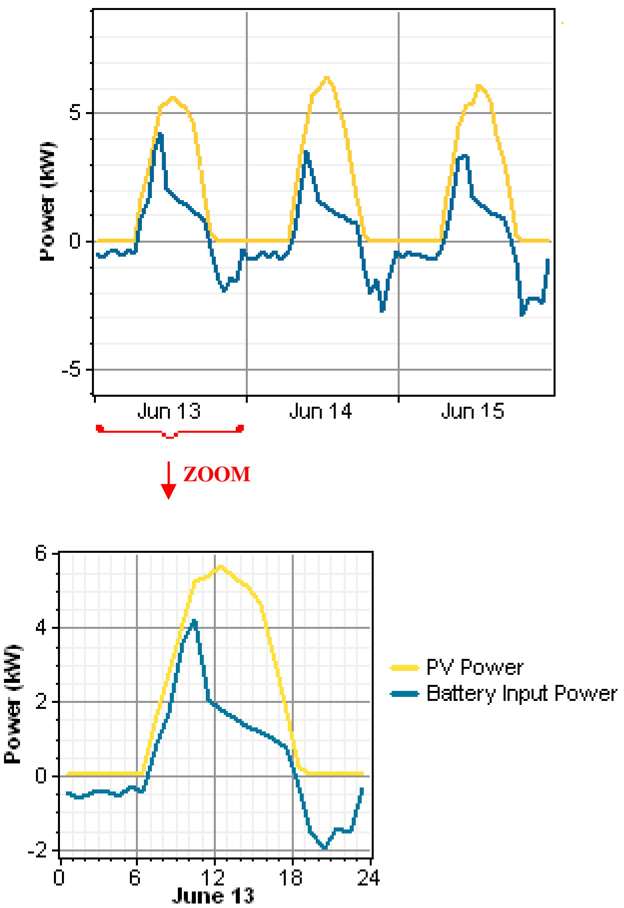


Fig. 17 Time evolution of the PV output and input power of the battery, along three days of June

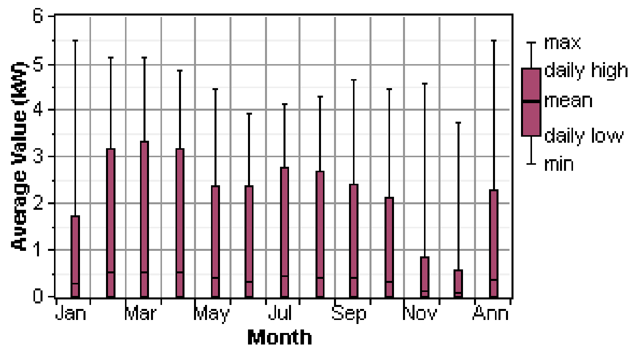


Fig. 19 Excess electrical production monthly averages

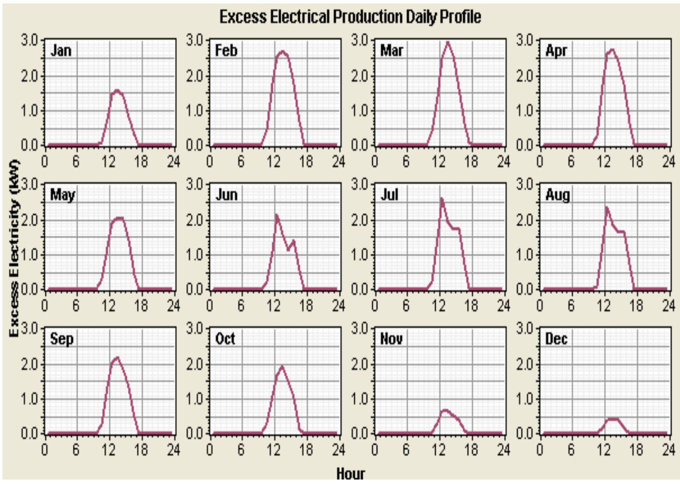


Fig. 20 Excess electrical production daily profile

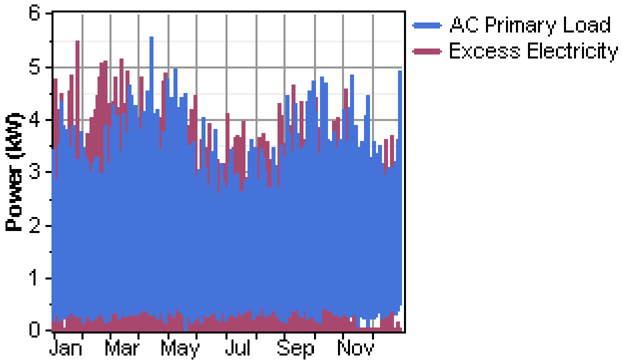


Fig. 18 Annual hourly evolution of load and electricity access

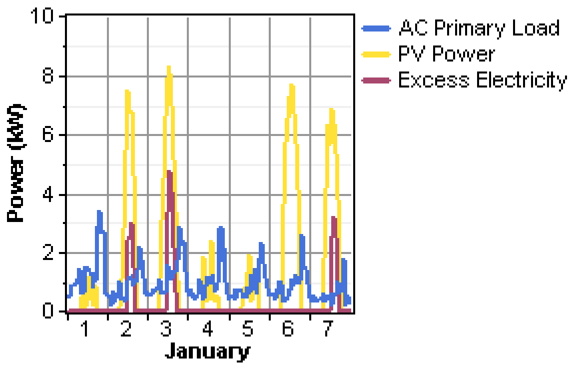


Fig. 21 AC primary load, PV power and electricity excess

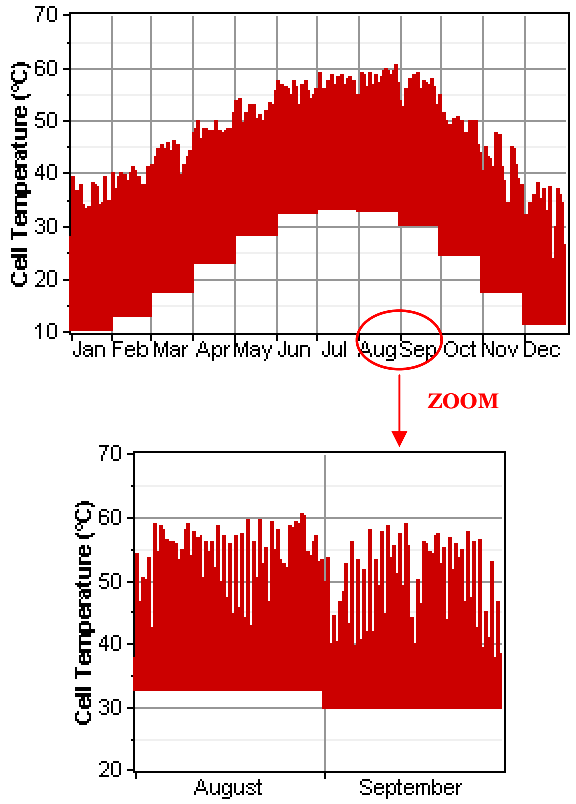


Fig. 22 Annual hourly evolution of cell temperature

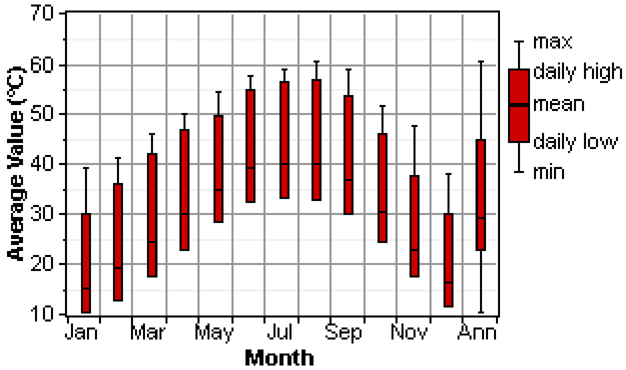


Fig. 23 PV cell temperature monthly averages

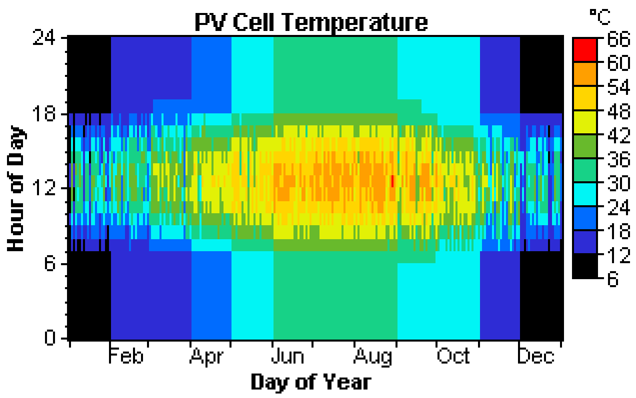


Fig. 24 Cell temperature DMap

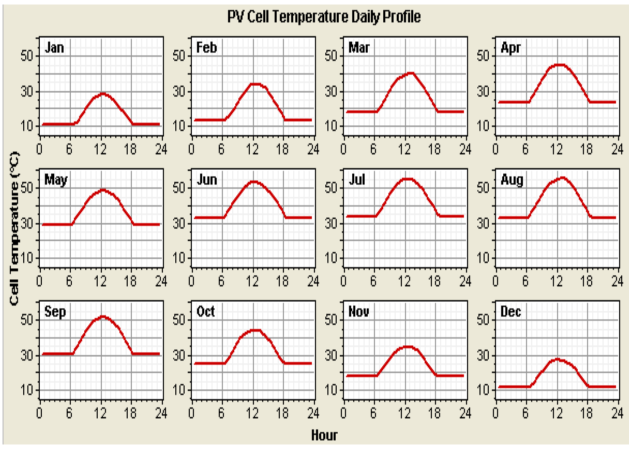


Fig. 25 PV cell temperature daily profile

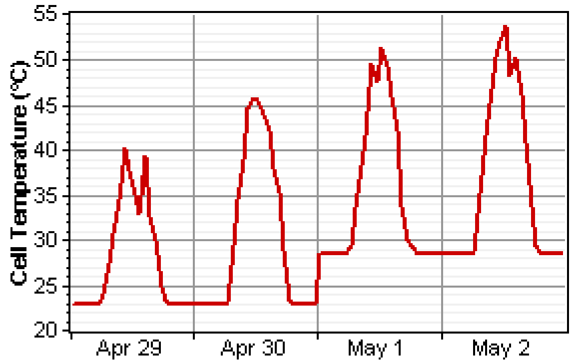


Fig. 26 Illustration of cell temperature fluctuation

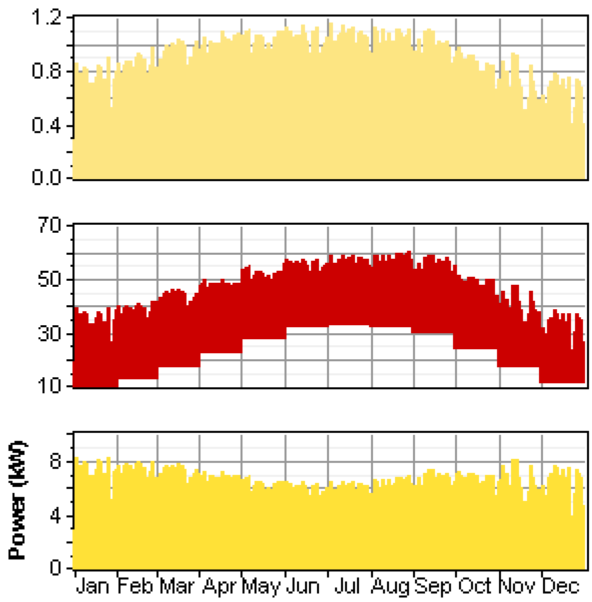


Fig. 27 Annual hourly evolution of global solar, cell T° and PV power

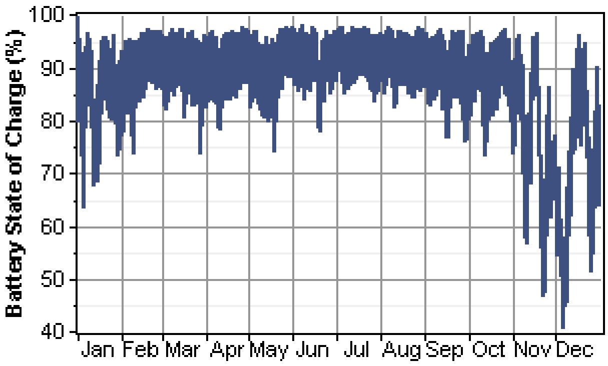


Fig. 28 Battery state of charge

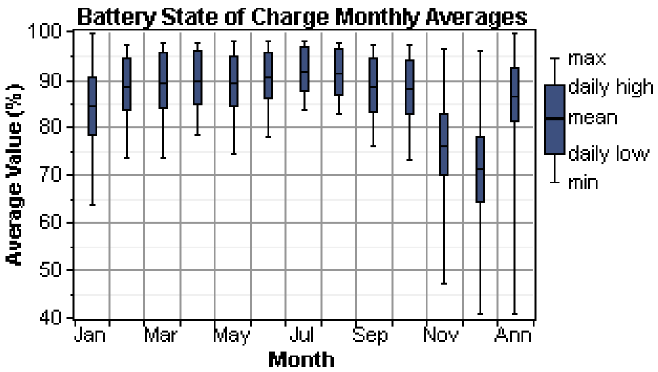


Fig. 29 Battery state of charge monthly averages

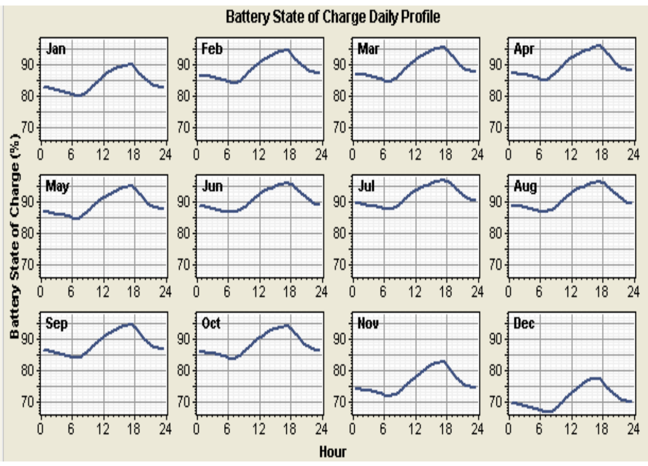


Fig. 30 Battery SOC daily profile

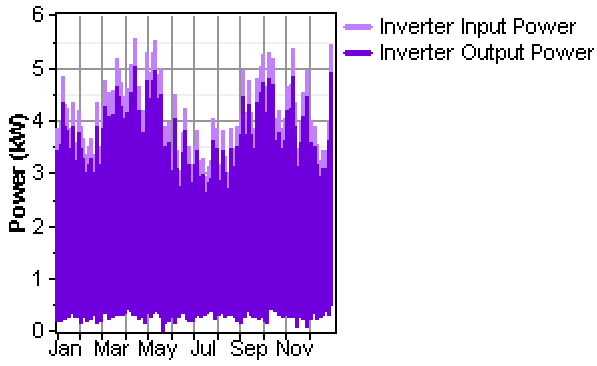
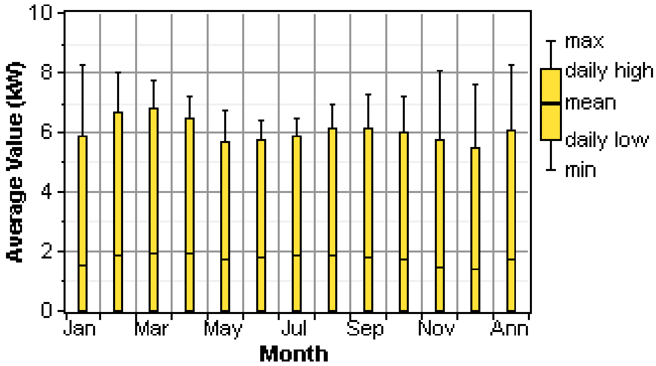
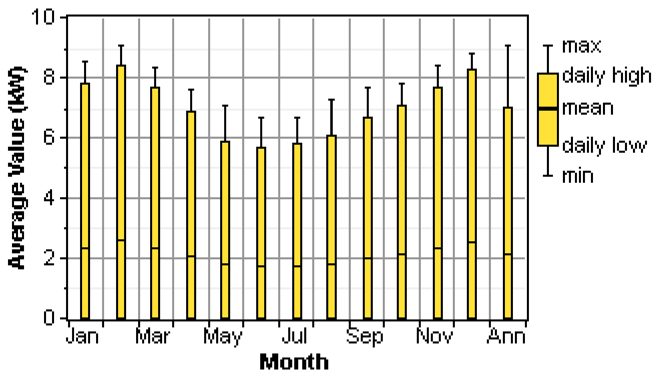


Fig. 31 Inverter input/output power



a) No inclined



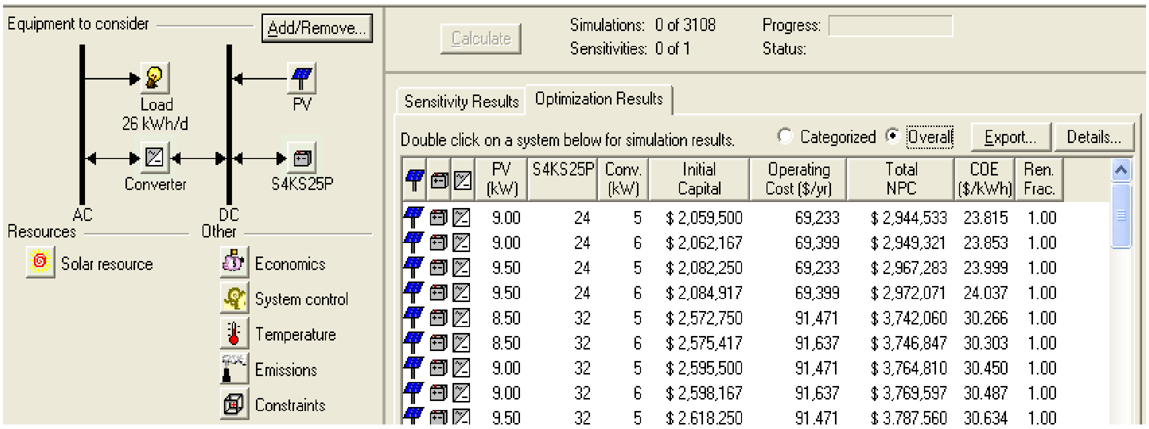
b) Optimal inclination = latitude of the location

Fig. 32 PV array power output monthly averages

TABLE I
TINDOUF GEOGRAPHICAL DATA

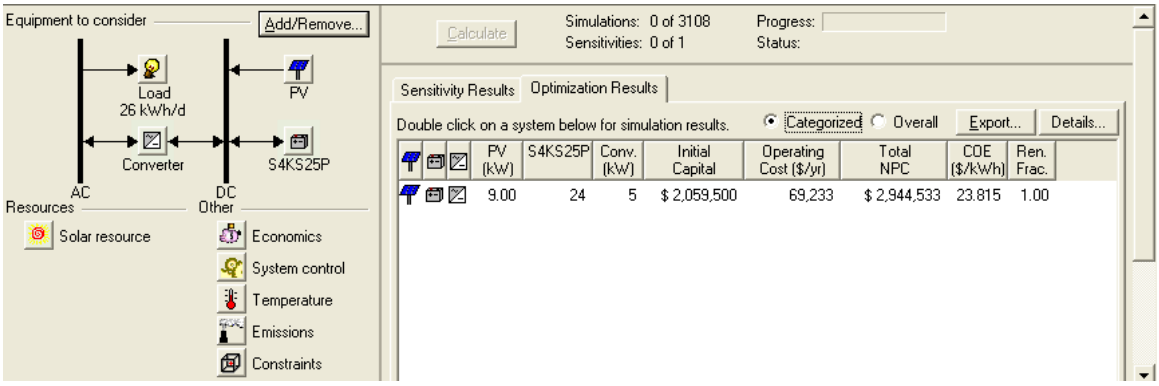
Caracteristics / Site	Longitude (°)	Latitude (°)	Altitude (m)	Geographical location
Tindouf	**8,14 W**	**27,40 N**	**386**	**Desert**

TABLE II
OVERALL PV POWER SYSTEM FOR THE SPECIFIED LOAD



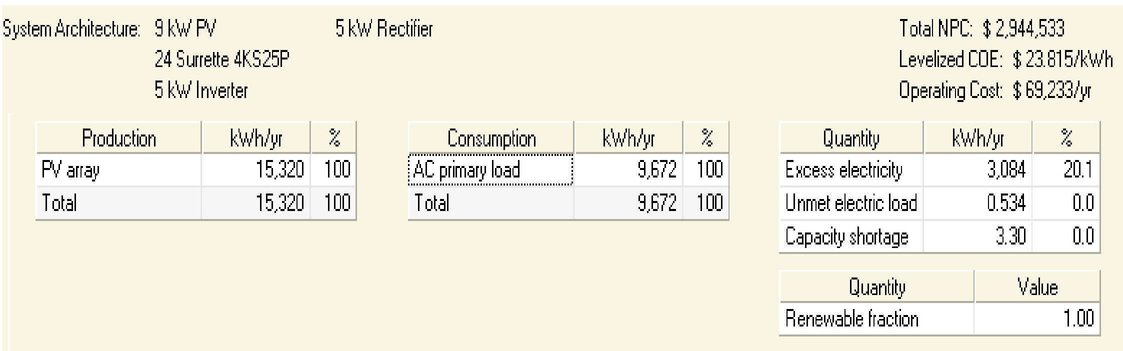
PV (kW)	S4KS25P	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.
9.00	24	5	$ 2,059,500	69,233	$ 2,944,533	23.815	1.00
9.00	24	6	$ 2,062,167	69,399	$ 2,949,321	23.853	1.00
9.50	24	5	$ 2,082,250	69,233	$ 2,967,283	23.999	1.00
9.50	24	6	$ 2,084,917	69,399	$ 2,972,071	24.037	1.00
8.50	32	5	$ 2,572,750	91,471	$ 3,742,060	30.266	1.00
8.50	32	6	$ 2,575,417	91,637	$ 3,746,847	30.303	1.00
9.00	32	5	$ 2,595,500	91,471	$ 3,764,810	30.450	1.00
9.00	32	6	$ 2,598,167	91,637	$ 3,769,597	30.487	1.00
9.50	32	5	$ 2,618,250	91,471	$ 3,787,560	30.634	1.00

TABLE III
OPTIMUM PV POWER SYSTEM FOR THE SPECIFIED LOAD



PV (kW)	S4KS25P	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.
9.00	24	5	$ 2,059,500	69,233	$ 2,944,533	23.815	1.00

TABLE IV
MAIN RESULTS



System Architecture: 9 kW PV, 24 Surrette 4KS25P, 5 kW Inverter, 5 kW Rectifier

Total NPC: $ 2,944,533
Levelized COE: $ 23.815/kWh
Operating Cost: $ 69,233/yr

Production	kWh/yr	%
PV array	15,320	100
Total	15,320	100

Consumption	kWh/yr	%
AC primary load	9,672	100
Total	9,672	100

Quantity	kWh/yr	%
Excess electricity	3,084	20.1
Unmet electric load	0.534	0.0
Capacity shortage	3.30	0.0

Quantity	Value
Renewable fraction	1.00