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ORIGINAL RESEARCH

A combined simulation and experimental analysis the dynamic performance of a 2 kW photovoltaic plant installed in the desert environment

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Abstract in this article, we present the study and results for the installation of a mini-photovoltaic power plant of 2 kW installed in the desert region (Applied Research in Renewable Energy (URAER), Ghardaia in southern Algeria during 15 days (14–31 January 2016). The objective is to compare Homer software simulation and experimental recorded data, to characterize and to evaluate the dynamic performance and energy balance of a photovoltaic plant composed of a PV generator, a battery storage and regulator which has the role of protecting the battery and management system operation face the climatic variations in desert region.

Keywords Stand-alone photovoltaic system · Homer · Acquisition · Desert environment

Introduction

Depletion of fossil energy resources, environmental problems, and the considerable increase in energy requirements, development of new energy resources is one of the priorities of the energy political of many countries. Renewable energy is an environmentally friendly alternative to fossil fuels [1, 2, 3].

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Photovoltaic solar energy contributes significantly to sustainable development in remote and isolated areas of the electrical distribution network. Mini solar power plants offer a very interesting solution for the electrical power necessary for the development of these regions. In the process, they reduce the negative impact of diesel on the environment [4, 20, 21].

The work that was defined for this study concerns a stationary application of 2 kW photovoltaic plants, isolated from the network. The objective set is to study the performance of a system and evaluate the potential of an energy conversion system using sources, PV generator and batteries. Data acquisitions monitoring and performance Analysis each hour, then processed to calculate the energy report for analyzing and interpreting the results. During this monitoring period are measured and analyzed daily parameters of the system, such as: irradiation, voltage, current and power generation for each mini central compound (PV Generator, Batteries, inverter and load consumption). This work also presents a modeling and simulation of mini-central conversion system applied to the isolated site Ghardaia in Algeria using Homer Software.

Local of study

All studies presented in this work were performed in the field of Applied Unit Research in Renewable Energy URAER, Ghardaia, Fig. 1, which is a region situated in the Middle-southern of Algeria (Latitude 32°36′ N, Longitude 3°81′ E, Altitude 600 m). This region is characterized by High ambient temperature in the summer and high solar irradiance potential [5] [6].

Fig. 1 Geographic location of Ghardaia site

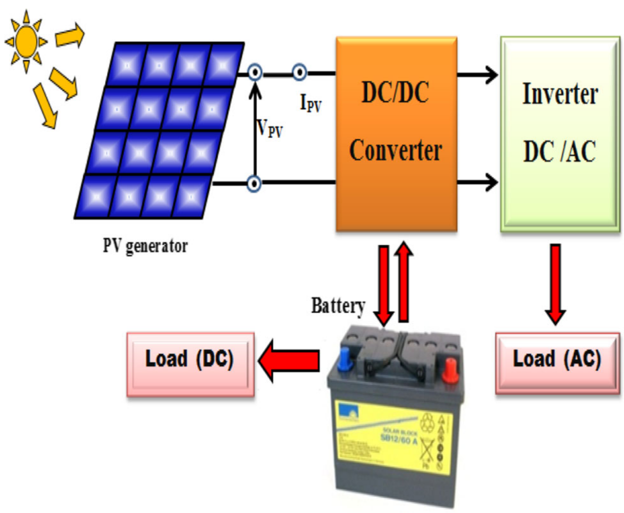


Fig. 2 Block diagram of an autonomous photovoltaic system

The PV system

The Fig. 2 shows the functional diagram of the autonomous photovoltaic system. It consists of the elements: PV generator, battery storage, regulator to control the battery and Inverter connected to the consumption charge [7, 8, 22, 23].

Mathematical modeling

Photovoltaic array output modeling

A PV array is a group of various PV modules which are electrically connected in series and parallel to give the required current and voltage. The equivalent circuit for the solar module organized in N_p parallel and N_s series is presented in Fig. 3 and the terminal equation for the current and voltage of the PV panel becomes as follows [9–11, 22, 23]:

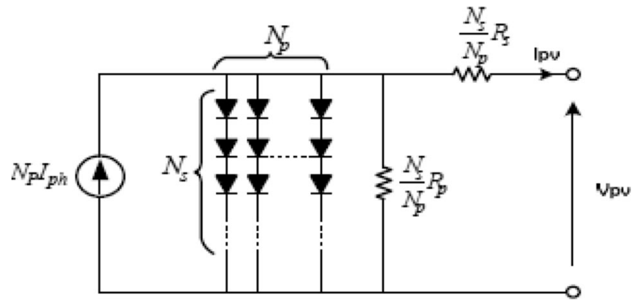


Fig. 3 Electrically equivalent of solar array circuit

$$I = N_p I_{ph} - N_p I_s \left\{ \exp\left[\frac{q}{KT} \left(\frac{V}{N_s} + \frac{R_s I}{N_p} \right) \right] - 1 \right\} - \frac{N_p}{R_p} \left(\frac{V}{N_s} + \frac{R_s I}{N_p} \right) \quad (1)$$

I_{ph} is photocurrent, I_s is the reverse saturation current, q is the electron charge ($q = 1.6 \times 10^{-19}$C), K the Boltzmann's constant ($K = 1.38 \times 10^{-23}$), and T is the solar array panel temperature, R_s is the intrinsic series resistance of the solar cell, Rsh: is the equivalent shunt resistance. Where:

$$I_{ph} = \frac{G}{G_{ref}} \left(I_{phref} - \mu_{cc} (T_c - T_{cref}) \right) \quad (2)$$

I_{phref} is photocurrent under reference.

μ_{cc} Coefficient of sensitivity of the intensity to temperature.

T_c, T_{cref} The temperatures of the real cell and to the reference condition.

Storage modeling

The battery, whose role is to store energy and release it when the sunlight is insufficient; the mathematical lead acid battery model used is given by [24, 25]. It is modelled by putting in series an electromotive force corresponding to the open circuit voltage when it is charged E_b, a capacity indicating the internal capacity of a battery (C_b) and an internal resistance R_b, Fig. 4 gives the equivalent circuit. The terminal voltage of the battery is given by:

$$V_{batt} = E_b - R_b \times I_{batt} - V_{C_b} \quad (3)$$

Many different storage technologies can be utilized with photovoltaic systems. Research is currently being under taken into the use of ultra-capacitors as a means of energy

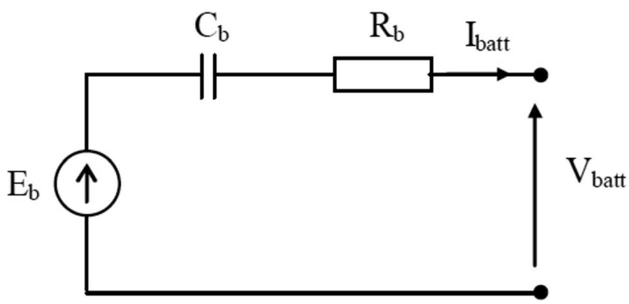


Fig. 4 Electrical model of lead acid battery

storage for photovoltaic systems. Battery technology remains the most popular choice. Nickel cadmium and nickel metal hydride batteries can be used, but the lead acid battery is still the most widely used storage method for stand-alone photovoltaic systems [26].

State-Of-Charge (SOC) is the ratio between the value of the battery and its value after discharge time [5, 6, 12, 13, 14].

$$\mathrm{SOC} = \frac{\text{Battery charge}}{\text{Battery capacity discharge}} \times 100\,\% \qquad (4)$$

Energy management strategy

The system aims are to ensure a maximum operating of the photovoltaic array and to make a decision on switching between different components (PV/battery/load) with correct operating of the battery to protect it against overcharge and deep of discharge. The batteries in a photovoltaic system operate in a cyclic way, discharging during the night and recharging during the day. The most recommended charging process in this case is the one with constant voltage and current limitation.

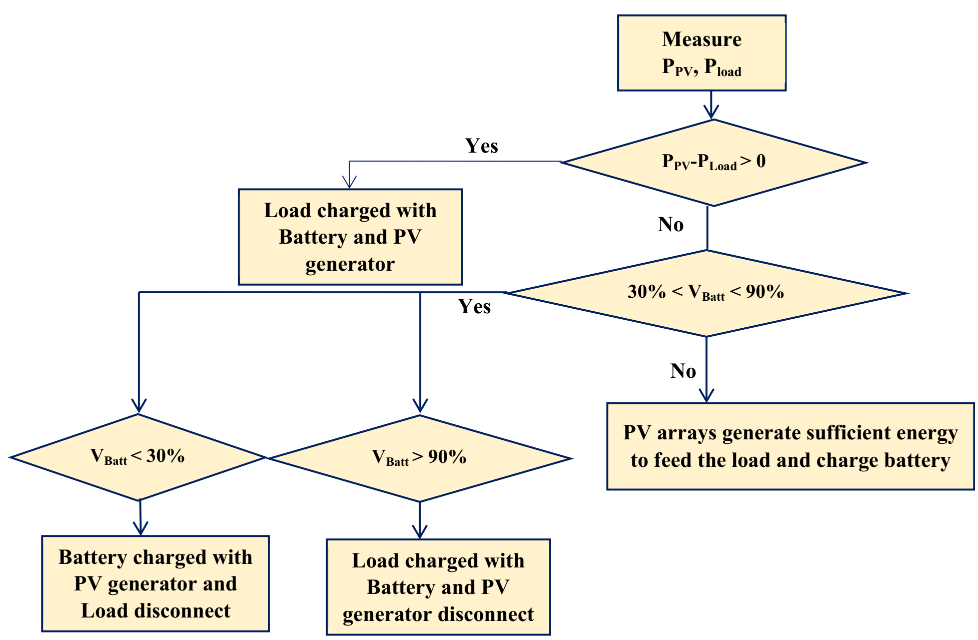
Figure 5 shows the flowchart of the strategy of load management strategy and description of energy produced and consumed by the various components for a stand-alone photovoltaic system. The objective was to improve the PV system reliability and minimize the batteries replacement. The study of the PV system's behavior required the input of three major parameters, solar irradiance (G), ambient temperature (T), the PV power and the power load power (P_{load}). For the autonomous PV system, the storage was conditioned.

The relays' switching is based on the following objectives:

- Satisfy the load with the required power.
- Protect the batteries against deep discharge and excessive charge. The battery state of charge (SOC) is maintained between two pre-fixed values (30 and 90 %).
- The unused energy provided by the panel is used to charge the battery' bank.

A good management of the charge and discharge of the batteries is necessary to prolong their life while ensuring optimum operating conditions. The objective of this management is the extraction of the energy required by the load, taking into account the load profile and the batteries state of charge at every moment and the availability of PV energy. For batteries charge, the available power P_{av} is function on the photovoltaic power P_{PV} and the load power P_{load}. The proposed standalone PV system operates in one

Fig. 5 Organigram of energy management strategy



of the following five operation modes, this cases are summarized as:

- Batteries charge: In this case, the PV arrays generate sufficient energy to feed the load and charge battery.
- Power compensation: In this case the energy available in PV array is not sufficient to supply the load, the battery bank supplements the energy required by the load.
- Battery discharge, it's occurs when there is no available energy at PV array. In this case, the battery bank supplies full load energy.
- In this case, the PV array generate sufficient energy to feed the load without the intervention of battery.
- In this case, no PV energy production and battery are completely discharged, and then the consumer is disconnected.

Homer software

HOMER (hybrid optimization model for electric renewable) is one of the global standard software in conception and deploying of micro-grids and distributed power systems that can include a combination of renewable energy multi sources, storage, and fossil-based energy (either through a local generator or through a power grid) developed by NREL (National renewable energy laboratory) in the US [15–18]. It can be useful in the evaluation of design options for off-grid and grid-connected power systems for remote, stand-alone generation applications [15–18]. There are three principal tasks that can be performed by HOMER: simulation, optimization and sensitivity analysis.

System components

In our PV/Battery energy system, there are four main components to the system: PV panels, Battery storage, a DC–AC converter, and the load. The HOMER system configuration is shown in Fig. 6.

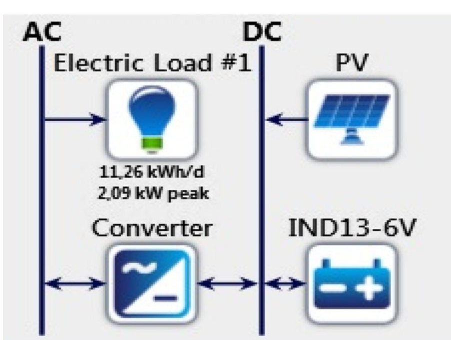


Fig. 6 PV/battery energy system architecture

Table 1 Optimal system architecture

	Characteristics
PV generator	2 kW (24 V)
Batteries	8 elements (235 Ah/6 V)
Inverter	3 kW

The optimal system architecture is given in the Table 1.

The simulation results of the PV installation are given by the HOMER Pro simulation model are shown below:

The annual irradiations on the site of Ghardaia are represented by the Fig. 7.

The daily irradiations on the site of Ghardaia are represented by the Fig. 8.

The daily power of PV array are represented by the Fig. 9.

The daily power at the input of the inverter is shown in Fig. 10.

The daily power at the output of the inverter is shown in Fig. 11.

The power output of the inverter maintains the same waveform at its input, but diminished in quantity due to losses within the same inverter.

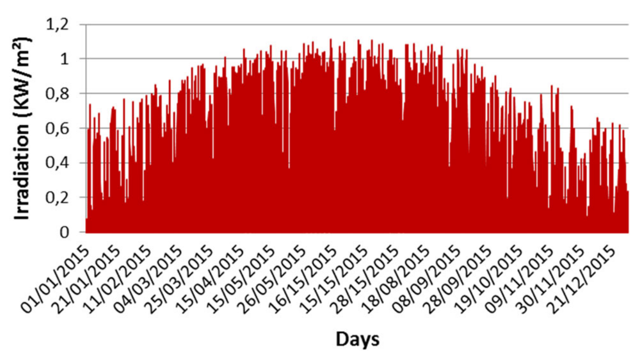


Fig. 7 Annual global profile of solar irradiation on the site of Ghardaia

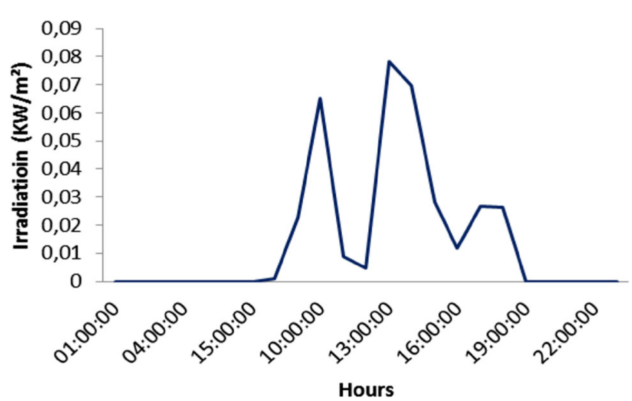


Fig. 8 The daily irradiation on the site of Ghardaia

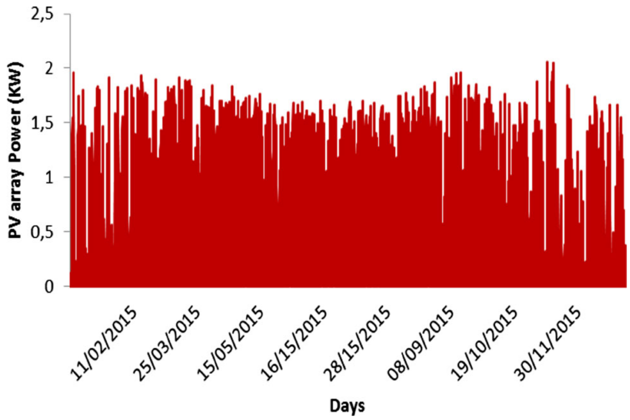


Fig. 9 The daily power of PV array

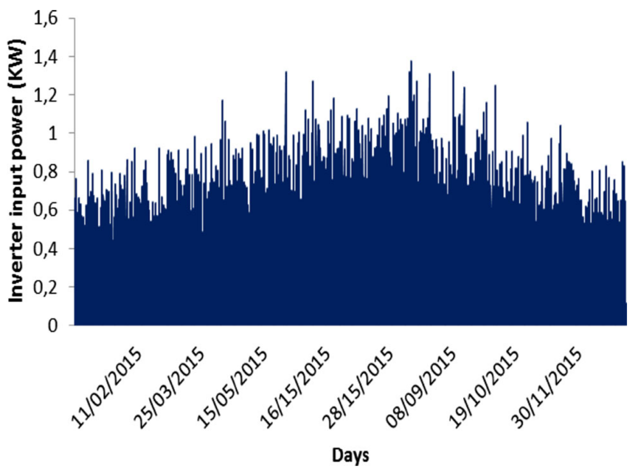


Fig. 10 The daily power at the input of the inverter

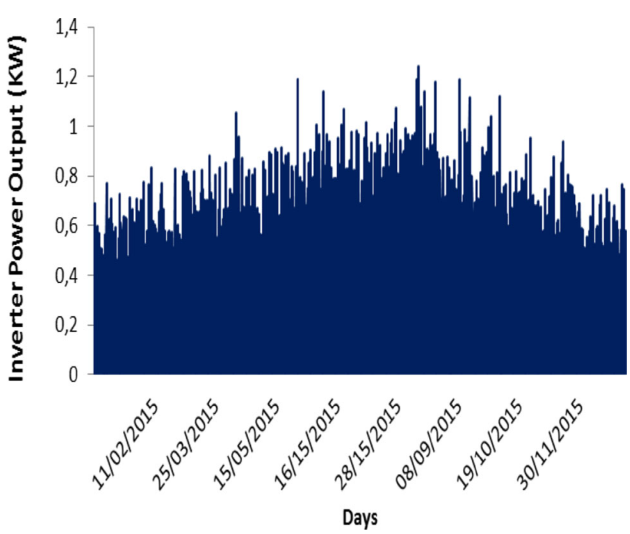


Fig. 11 The daily power at the output of the inverter

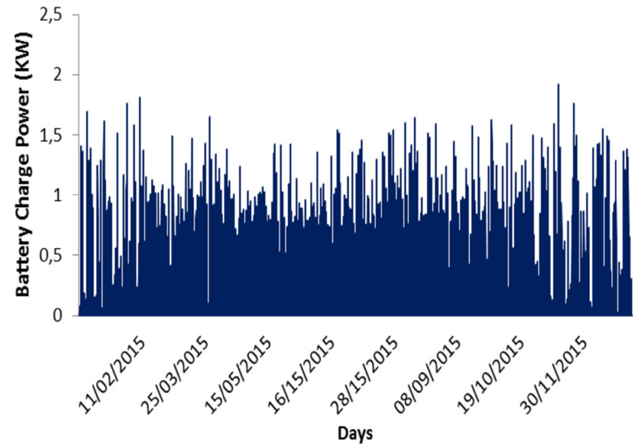


Fig. 12 Battery charge power

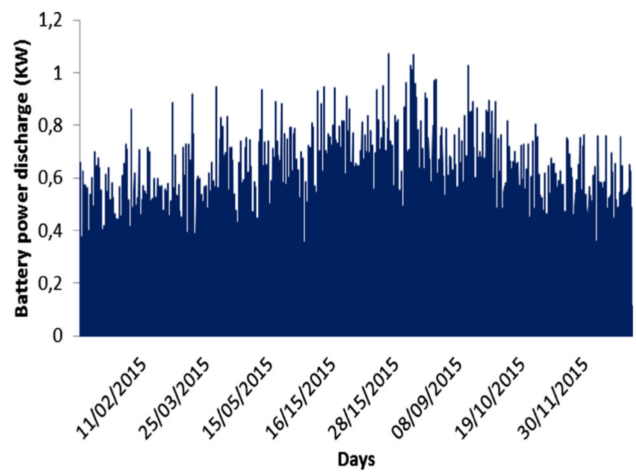


Fig. 13 Battery power discharge

Battery charge and discharge power are given in Figs. 12 and 13.

Distribution of daily power load demand are given in Fig. 14.

The daily PV generator variation with seasons is given by the Fig. 15 below.

The AC primary consumption daily profile with the seasons is as follows (Fig. 16).

We see in this figure, the battery charges in photovoltaic production period, taking place from 6.30 18.30, the battery power is positive along this period. The rest of the day the battery discharges, and it is that which covers the demand, its power in this case is negative. The discharging and recharging of the accumulator are imposed by the consumer and production systems.

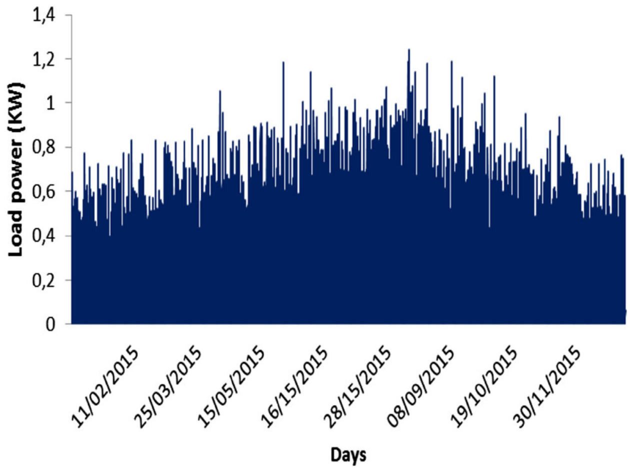


Fig. 14 Distribution of daily power load demand

Description of the mini central studied

Figure 17 displays the mini central studied in Ghardaia area. It divided by two fields; the first is based on the solar modules of 50 W/12 V, and the second on 100 W/24 V modules. The modules in both fields consist of photovoltaic cells based on monocrystalline silicon. Each mini plant, provided power 1 kW, the first consists of 20 module I-50 type modules manufactured by the company Isophoton, and the second consists of 10 modules of type I-100/24 (same manufacturer). Their characteristics are given in Table 2. The solar energy was Stored in 8 batteries (lead acid technology) used at night and not sunny. The rated voltage of the battery element used is 6 V with a nominal capacity of 235 Ah. The regulator protects the batteries by reducing the energy input in the case of sufficiently high voltage batteries. Also, it protects the batteries against deep discharge. A data acquisition system was installed in order to ensure the data collection of the various climatic parameters. For irradiation measurement, a CM11 Pyranometer type with a sensitivity equal to 4.57×10^{-6} V/ Wm^{-2} was used. The variation of used charges is:

– Refrigerator, agilent data logger and computer at night.
– PC and agilent data logger in the day.

In this experiment, Agilent 34970A Data Acquisition to control system was installed in order to make sure the follow-up of various parameters (climatic parameters, current and voltage of the PV array, storage and load) and to see their results in a desert environment [19].

For irradiation measurement, a CM11 Pyranometer type with sensitivity equal to 4.57×10^{-6} V/Wm^{-2} was used below, in Fig. 18 is given the set configuration set of the BenchLink Data Logger software.

The different instruments were connected to the channels (101–112) of the standard module 34901A to measure of all parameters necessary for the evaluation of the PV

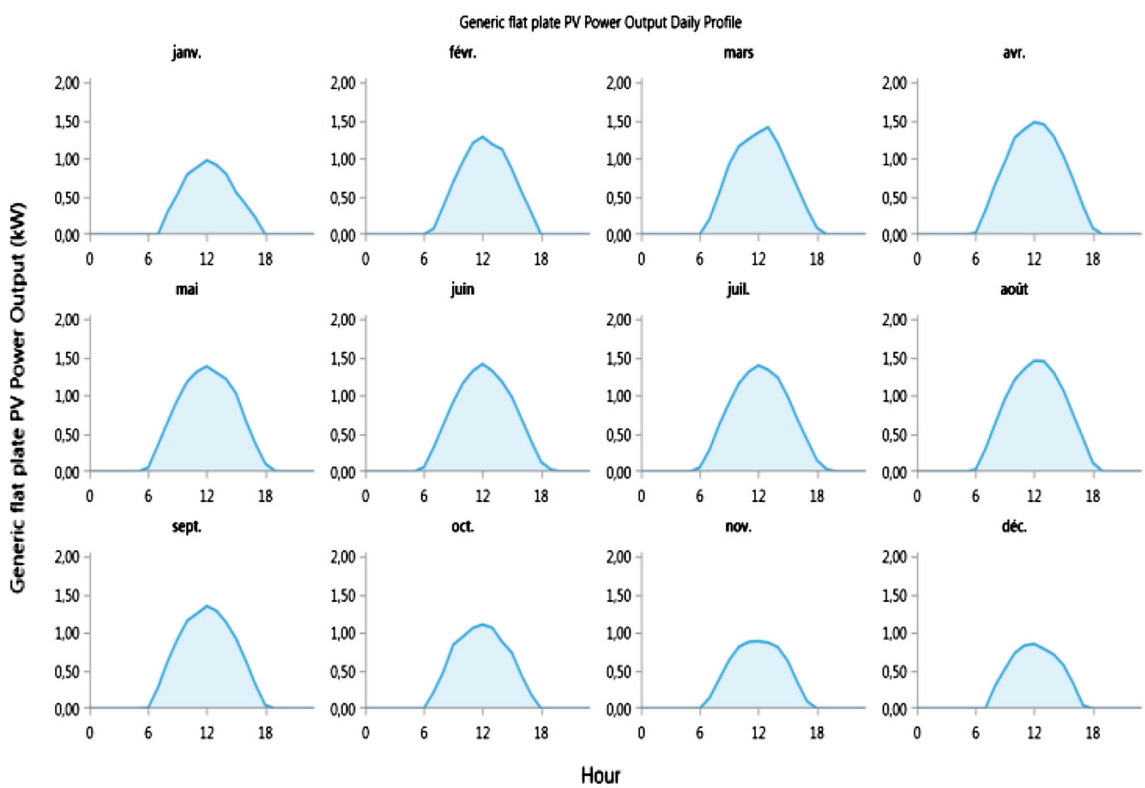


Fig. 15 The daily PV generator variation with seasons

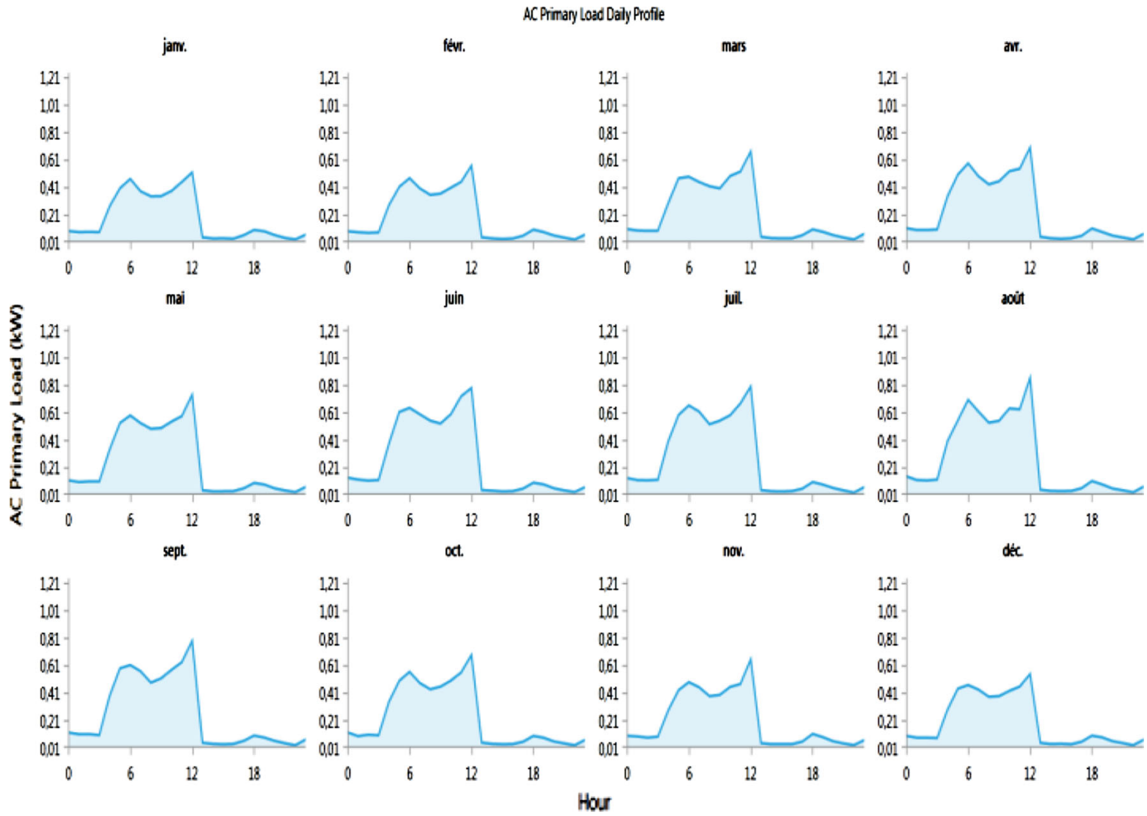


Fig. 16 Daily load profile according to the season's variation

system performance of each compound (irradiation, temperature, voltage, current and power).

The experimental results for 1 day (15 January 2016)

Data recorded collected during 1 day (15 January 2016) for weather and total in-plane radiation are presented below.

The measurement results of the 2 kW photovoltaic plants for 1 day (15 January 2016) are presented below.

Figures 19 and 20 show the voltage, current and power of PV generator.

Figures 21 and 22 show the voltage, current and power of the battery.

Figure 23 shows the input and output power of inverter and load demand current.

An average hourly variation of local solar irradiation to the production of PV output power during 7:00–18.00 for in 15 January 2016 at Ghardaia test site. It can be concluded that the production of PV output power is a function of solar irradiation and module working temperature. It increased with increasing solar irradiation and decreased with increasing module working temperature. These mean that solar irradiance and module working temperature play important factors in order to estimate energy production and degradation of the PV system. From Figs. 19 and 20, it was found that the production of total PV output power is in the range of 0–1 kWat the local solar irradiation varies between 0 and 500 W/m^2.

Energy balance

Figure 24 shows the energy balance of the system; these energy balances are obtained and calculated from measurements made during the given period. It takes the average daily value of this period.

Eb1 ch: Battery energy loading (group 1).
Eb1 disch: Battery energy unloading (group1).
Eb2 ch: Battery energy loading (group 2).
Eb2 disch: Battery energy unloading (group 2).
EbT ch: Total battery energy loading.
EbT disch: Total battery energy unloading.
Eg1: PV generator energy (group1).
Eg1: PV generator energy (group2).
EgT: Total PV generator energy.
E load day: load demand during the day.
E load night: load demand during the night.

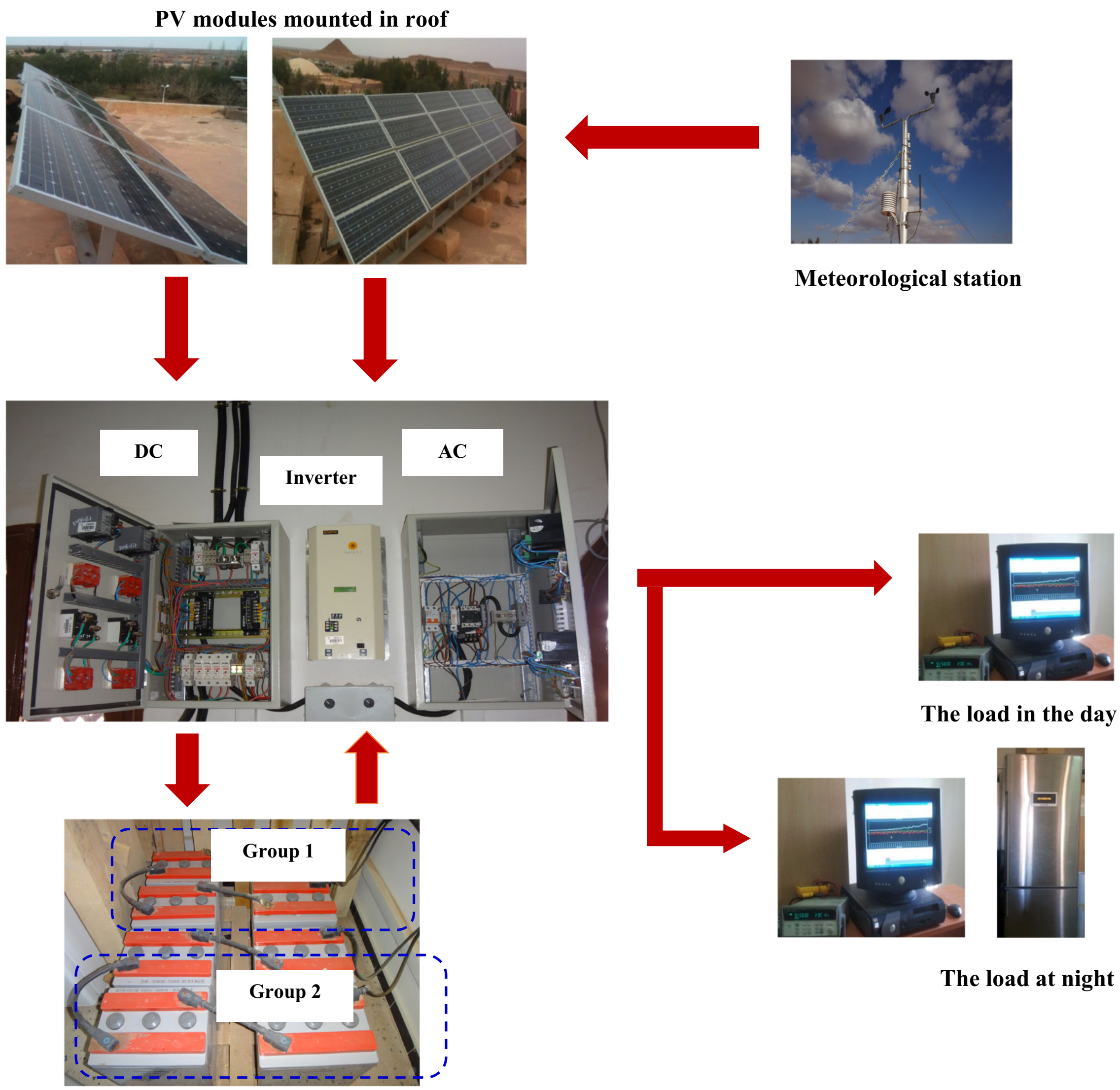


Fig. 17 Experimental autonomous PV system

Table 2 Module characteristics (I-50/12 V and I-100/24 V)

	Module I-50	Module I-100/24
Maximum power (P_m)	50	100
Short circuit current (I_{cc})	3, 27 A	3, 27 A
Open circuit voltage (V_{oc})	21, 6 V	43, 2 V
Current at MPPT (Im)	2, 87 A	2, 87 A
Voltage at MPPT (V_m)	17, 4 V	34, 8 V
Number of cells	36	72

The experimental results for 2 weeks (14–31 January 2016)

Data recorded collected during 2 weeks from 14 January 2016 to 31 January 2016 for weather and total in-lane radiation will be presented.

The measurement results of the 2 kW photovoltaic plants for 2 weeks (14–31 January 2016) are presented below.

Figures 25 and 26 show the voltage and current of PV generator.

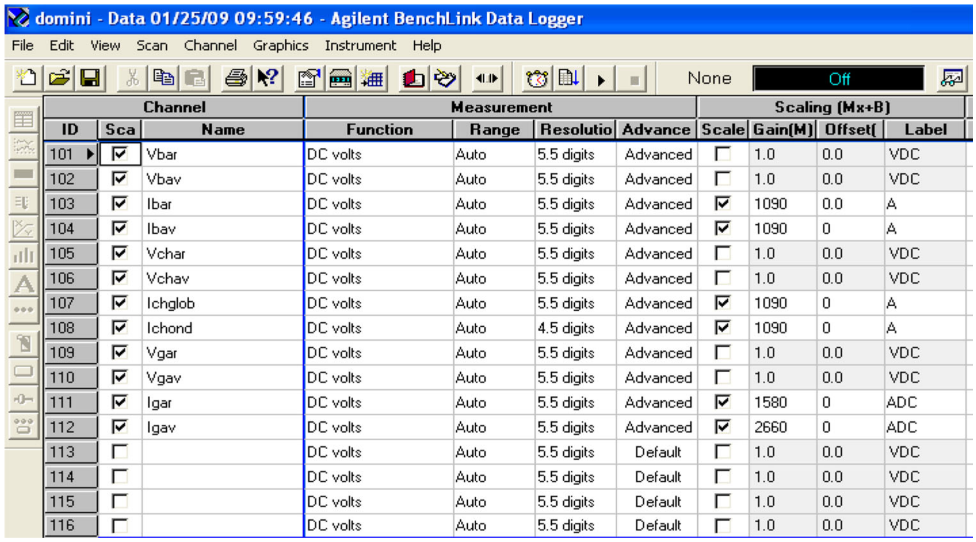
Figure 27 shows the power of PV generator.

Figures 28 and 29 show the voltage and current of batteries.

Figure 30 shows the power of battery.

Figure 31 show input and output power of inverter and load demand current.

An average hourly variation of local solar irradiation to the production of PV output power during 7:00–18.00 from 14–31 January 2016 at Ghardaia test site. It can be concluded that the production of PV output power is a function of solar irradiation and module working temperature. It increased with increasing solar irradiation and decreased



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Channel			Measurement				Scaling (Mx+B)			
ID	Sca	Name	Function	Range	Resolutio	Advance	Scale	Gain(M)	Offset(	Label
101	☑	Vbar	DC volts	Auto	5.5 digits	Advanced	☐	1.0	0.0	VDC
102	☑	Vbav	DC volts	Auto	5.5 digits	Advanced	☐	1.0	0.0	VDC
103	☑	Ibar	DC volts	Auto	5.5 digits	Advanced	☑	1090	0.0	A
104	☑	Ibav	DC volts	Auto	5.5 digits	Advanced	☑	1090	0	A
105	☑	Vchar	DC volts	Auto	5.5 digits	Advanced	☐	1.0	0.0	VDC
106	☑	Vchav	DC volts	Auto	5.5 digits	Advanced	☐	1.0	0.0	VDC
107	☑	Ichglob	DC volts	Auto	5.5 digits	Advanced	☑	1090	0	A
108	☑	Ichond	DC volts	Auto	4.5 digits	Advanced	☑	1090	0	A
109	☑	Vgar	DC volts	Auto	5.5 digits	Advanced	☐	1.0	0.0	VDC
110	☑	Vgav	DC volts	Auto	5.5 digits	Advanced	☐	1.0	0.0	VDC
111	☑	Igar	DC volts	Auto	5.5 digits	Advanced	☑	1580	0	ADC
112	☑	Igav	DC volts	Auto	5.5 digits	Advanced	☑	2660	0	ADC
113	☐		DC volts	Auto	5.5 digits	Default	☐	1.0	0.0	VDC
114	☐		DC volts	Auto	5.5 digits	Default	☐	1.0	0.0	VDC
115	☐		DC volts	Auto	5.5 digits	Default	☐	1.0	0.0	VDC
116	☐		DC volts	Auto	5.5 digits	Default	☐	1.0	0.0	VDC

Fig. 18 Agilent bench kink data logger software configuration [8]

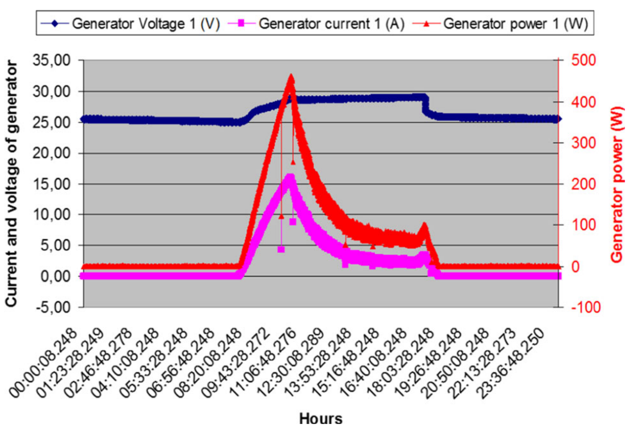

Fig. 19 Voltage, current and power of PV generator (group 1)

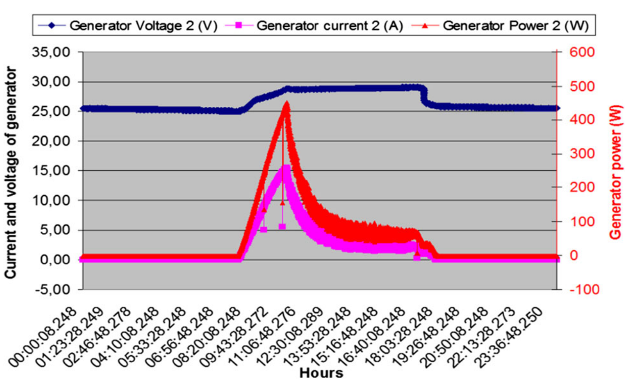

Fig. 20 Voltage, current and power of PV generator (group 2)

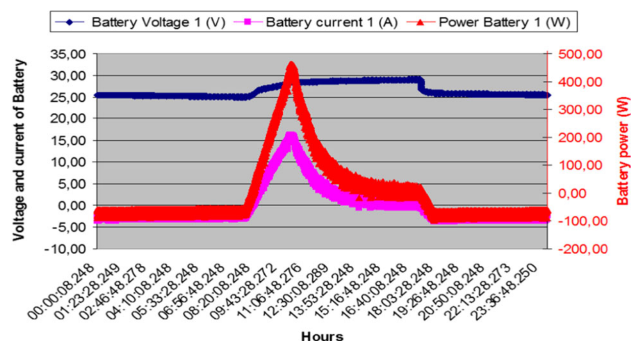

Fig. 21 Voltage, current and power of Battery (group 1)

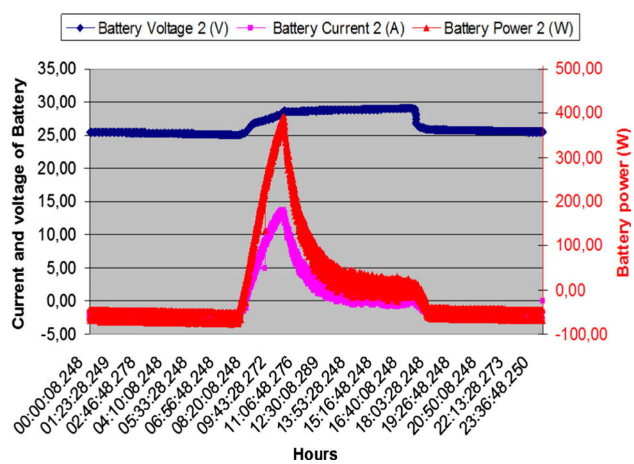

Fig. 22 Voltage, current and power of Battery (group 2)

with increasing module working temperature. These mean that solar irradiance and module working temperature play important factors in order to estimate energy production and degradation of the PV system. From Figs. 19 and 20, it was found that the production of total PV output power is in the range of 0–1 kWat the local solar irradiation varies between 0 and 500 W/m^2.

We can observe that the hourly global parameters performance of PV plant (voltage, current and power) are more significant between 10.00 and 14.00 h. The PV power

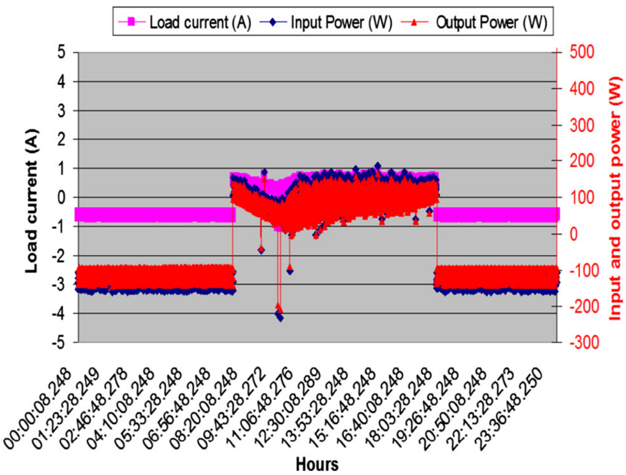

Fig. 23 Input and output power of inverter and load demand current

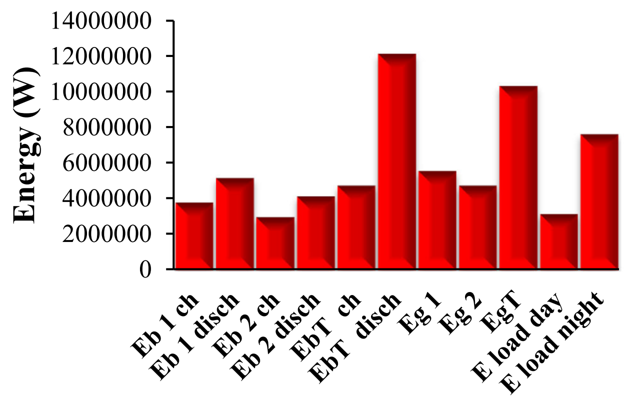

Fig. 24 The energy balance of the mini central studied

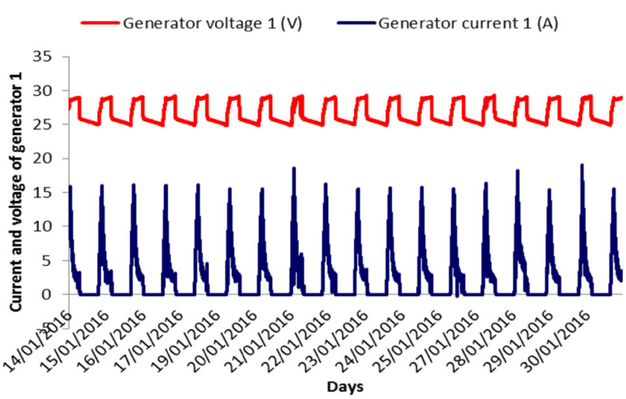

Fig. 25 Voltage and current of PV generator (group 1)

production takes the maximum value at 12.00 and equal to zero at night, which illustrate the effect of weather conditions on the efficiency of PV panels and the relationship between the radiation and the output power of PV panel.

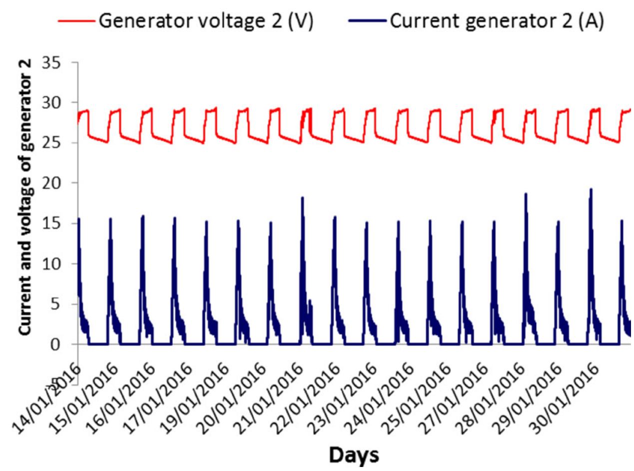

Fig. 26 Voltage and current of PV generator (group 2)

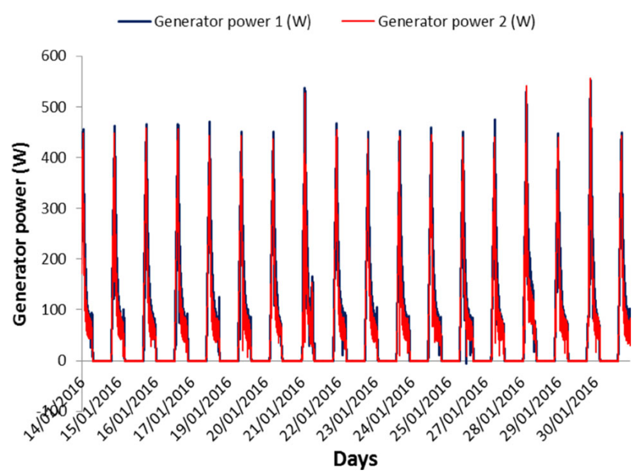

Fig. 27 PV generator Power

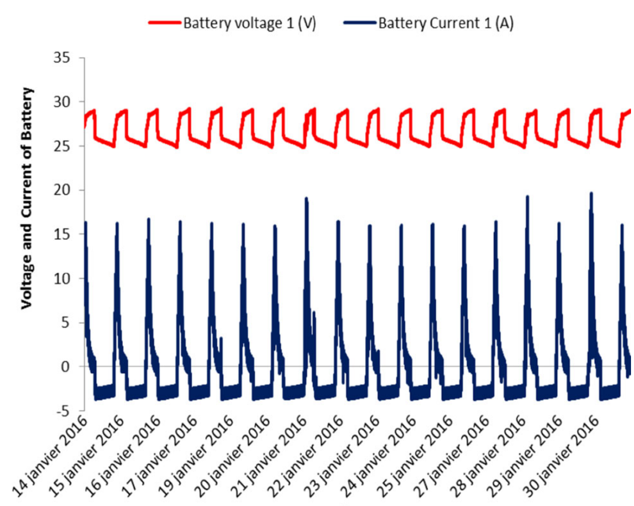

Fig. 28 Voltage and current of battery (group 1)

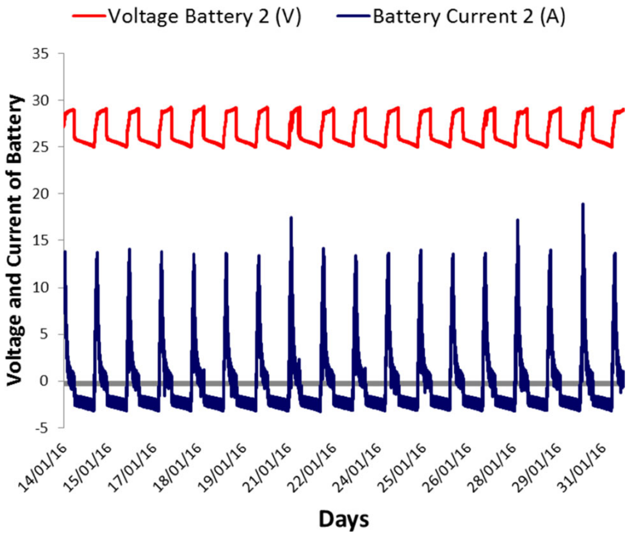

Fig. 29 Voltage and current of battery (group 2)

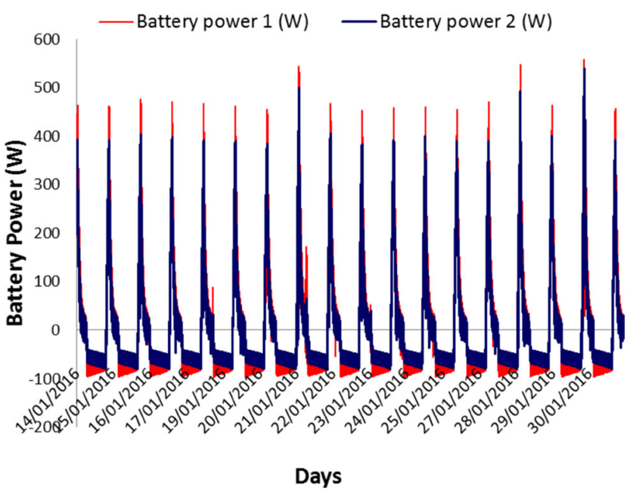

Fig. 30 Battery power

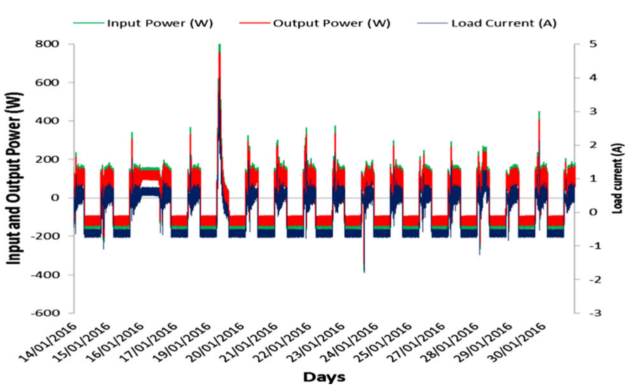

Fig. 31 Input and output power of inverter and load demand current

Conclusion

The focus of this paper is on the study and the presentation of results for the installation of a mini-photovoltaic power plant of 2 kW installed and monitored between 15 January 2016 to 31 January 2016 at the Applied unite research in renewable energy in the south of Algeria in the desert region (Ghardaia). Simulation using Homer software was done to optimize and evaluate energy balance and was validated with the experimental results to analyze the photovoltaic system performance parameters under the effect of the climatic conditions in the desert environment.

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