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Experimental Study of the Combined RES-Based Generators and Electric Storage Systems for Public Buildings

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Abstract

In the present paper, a new approach to the management of energy resources in the Research and Technology Centre of Energy (CRTEn -Tunisia) is proposed and evaluated by the monitoring of a PV installation realized for the cooperation project DE.DU.ENER.T, using renewable energy and economic criteria. The aim of this project is to improve energy efficiency order to minimize the electricity cost consumed at the CRTEn laboratory. According to the bills of electricity received, we noticed that there is a high consumption of electrical current. So, we targeted to install a photovoltaic field of 12KWc to reduce these bills by using the sustainable, green and clean sources.

A theoretical study of the PV system sizing realized in order to know in the first hand the compatibility between the different equipment of this installation and to compare the results with those found by the *SMA Sunny Design* and *PV*SOL* software in the second hand.

The experimental results show that the performance factor of the proposed system is 84.6%. Meanwhile, the cost of the energy generated by the proposed system is 0.045 USD/kWh, which means that the payback period, is about 11 years. The conclusion from this study is that the price of energy generated by PV systems in Tunisia is lower than the subsidized price of energy generated by fossil fuel.

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Keywords: Heat Transfer, Hybrid Energ System, Renewable Energy, Photovoltaic Panel, Simulation.

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Nomenclature

Symbol	Description	Unit
$U_{mppt,max}$	Maximum input Dc voltage to the inverter	V
$U_{mppt,min}$	Minimum input Dc voltage to the inverter	V
U_{mpp}	Maximum voltage of the PV panel	V
U	DC Voltage drop	V
I, I_{Mpp}	Maximum current of the panel	A
L	Cable length	m
u	AC Voltage drop	V
b	Coefficient	No unit
s	Cable section	mm^2
$cos\phi$	Power factor	No unit
λ	Linear reactance	Ω/m
I_b	Maximum output current of the inverter	A
Δu	Relative voltage drop	V
U_0	Nominal voltage	V
ΔV	Voltage difference	V
βV_{0C}	Temperature coefficient	%/°C
V_{string}	String voltage	V
ΔT	Temperature difference	°C
V_{max}	Maximum input voltage to the inverter	V
$I_{string\ input}$	Maximum input current per string	A

1. Introduction

In 2016, the annual growth rate of the Tunisian electricity demand was 17.8% due to the growth in population and industry sectors. However, according to the Ministry of Economic report published in 2014, the electricity production is reported at 17,823 GWh. This energy is much-generated using fossil fuel, while the renewable energy resources (RES)-(Wind energy and PV) are limited to 4% of the Tunisian electricity balance without biomass. Excluding biomass, the share of RES in final energy consumption should reach 6.9% in 2020 and 12.4 % in 2030. This situation shows that renewable energy studies must be done for Tunisia Regions in order to encourage the investment in this field. Such studies must start by investigating and evaluating renewable energy systems in terms of economic and technical criteria [1-3].

The annual solar energy amount in the south area of Tunisia is almost equivalent to hundreds of thousands of times the Tunisian's total generation capacity. Wind turbine and PV systems provide perhaps the main way to develop and use solar energy. In addition, it is not subject to geographical limitations and it does not involve the consumption of any fuel or emitting greenhouse gases. At the same time, it can be operated unmanned, and require short construction periods. With the increasing of PV systems use, it is essential to know the impact of meteorological parameters such as temperature, humidity, dust and wind speed on PV system performance [4]. Several studies have been conducted in the MENA region, the Gulf Council Countries (GCC) region and elsewhere to investigate the effects of environmental factors on the PV system performance [5]. However, these effects are geographical site precise hence; conscious study should be conducted for each area.

In [5, 6] Previous studies claimed that MENA region has a good solar energy potential and therefore, any PV system investment in this area is expected to be feasible. However, according to [7, 8], the performance of PV system is a location dependent variable where the climate and installation field nature strongly affect it. The performance of

PV system is the ratio of the actual performance to the theoretical performance. Consequently, this information is extremely important for the systems design, control and planning in any region. In [9] performances of PV systems were reported in a tropical region such as Malaysia. According to these researches, the productivity of these systems is in the range of (2.1–2.5) kW h/kWp per day with a performance factor in the range of (73 –77%). In the meanwhile, in [13] the productivity of PV systems installed at a subtropical region such as India is reported in the range of (2.49–4.5) kWh /kWp per day. Same performance study is done for a Mediterranean region in [10] and it is reported that the productivity of PV system is about 4 kWh/kWp per day. Study the renewable energy potential, claimed solar, and wind energy sources are the best choices for electricity generation in MENA Region.

In addition, it is reported in [11] that the productivity of PV system in France is 3.2 kWh/kWp per day, while such a system produced 2.44 kWh /kWp with a performance factor of 78% in Belgium according to [12]. Same studies were done for African desert and other zones in the world reported in [13-15]. Based on all of these researches, it is important to investigate the performance of PV system in Tunisia in order to provide important technical recommendation for those who are interested in PV system research and installation in this region and nearby regions.

Based on that, the aim of this paper is to design and evaluate the performance of a grid-connected PV system in Tunisia. Actual meteorological data are used in this research. These data contain the hourly global solar radiation, the diffuse solar radiations and the hourly ambient temperatures. The proposed PV system design is done using *PV*Sol* and *PV*System* software. After that, the system is implemented practically and evaluated. The proposed system is equipped with a grid tied inverter that used to synchronize the frequency and the phase of the power generated specific software. The annual average solar radiation in Tunisia is 2.600 kWh/m^2 in the south region. However, the minimum value of solar radiation is recorded in the cold season at the north zone. Therefore, most of the global solar radiation is from a direct radiation. The temperature is in the range of 12–50 °C with the minimum values in the cold season, while the maximum value is in the hot season periods with an average value of 37 °C. Based on the measured solar radiation, it is expected that PV system productivity will be promising in this zone.

For exploring the opportunities given by the Hybrid Renewable Energy (HRES) generators coupled with innovative storage systems, the authors have built two different prototypes in Valderice (Italy) and is in Borj-Cedria Techno-Park (Tunisian Prototype) in the framework of the international cooperation project DE.DU.ENER.T. [13-15]. Both prototypes comprise:

- A Photovoltaic Panel Generator;
- A micro-wind generator;
- An electric consumption center;
- A Battery Energy Storage System (BESS).

2. Prototypes

2. 1. Description of the prototypes

The Tunisian prototype of the DE.DU. ENER.T has been installed near the Laboratory of Energy and Thermal Processes (LPT), a part of the Research and Technology Centre of Energy (CRTEn), to reduce the energy consumption consumed from the grid by this laboratory (Fig. 1), and it composed by a 12 kWc of photovoltaic field and a 1 kWc of wind turbine. This work will focus only on the study and simulation of the PV installations for the DE.DU.ENER.T. Project [13, 14].

2. 2. Works Methodology and Laboratory Equipment

After identifying the different equipment of the LPT laboratory, we tried to identify the optimal operating mode (number of unit, operating hours...) and identified the different electrical characteristics (current, voltage, power...) for each appliance to determine the real power consumption in this building (LPT laboratory) and the higher energy consuming equipment. The development of control strategies asks for a computationally efficient energy model of a building under study [9-10]. Instead, a dedicated energy meter has been used for measuring all the energy consumption of the laboratory offices. Thus, in this case, real data have been used. Consequently, after determining these powers, the photovoltaic power to install is determined by the following expression:

$$\text{PV Power} = \sum \text{Annualy Power} \Big/ \text{Basic Consumption} \tag{1}$$

(a)

(b)

Fig. 1. DE.DU.ENER.T. Platform (a) and the PV- Wind CRTEn installation (b).

Table 1. Electrical characteristics of PV module

Characteristics	Units	STC Conditions	NOCT Conditions
Maximum Power	W	250	181.6
Voltage at Pmax	V	28.9	26.4
Current at Pmax	A	8.66	6.91
Open circuit voltage	V	37.6	34.8
Short circuit cuurent	A	9.29	7.50

2.3. Theoretical sizing of the equipment for the Tunisian Prototype

- Photovoltaic Module

We have chosen to install Yingli Solar Monocrystalline Photovoltaic Panels of 250 W, tinted in black because in this case, it becomes more selective and we will have a maximum yield of 15.3%. We must make sure that voltage delivered by the PV field belongs to the MPPT voltage range of the inverter. If it does not, the installation may have a power loss. This MPPT voltage range will also have an impact on the number of PV panels in string [24, 25]. The following equations should be used to determine the minimum and maximum number of PV panels in string [21]:

$$\text{Maximum number of panels} = E\left(\frac{\text{Umppt, max}}{\text{Umpp*1,15}}\right) \tag{2}$$

$$\text{Minimum number of panels} = E\left(\frac{Umppt,\min}{Umpp*0,95}\right) \tag{3}$$

The theoretical calculation has given us a minimum number of 16 panels and a maximum number of 24 panels, and we will connect to the A input of the inverter 32 panels according to tow (2) strings and to the B input 16 panels into a single string (Fig. 2). The sizing of an inverter per string is based on three criteria: Power compatibility, Maximum voltage compatibility, Current compatibility.

	Input A:	Input B:
Number of strings:	2	1
PV modules per string:	16	16
Peak power (input):	8.00 kWp	4.00 kWp
Typical PV voltage:	432 V	432 V
Min. PV voltage:	387 V	387 V
Min. DC voltage (Grid voltage 220 V):	150 V	150 V
Max. PV voltage:	647 V	647 V
Max. DC voltage:	1000 V	1000 V
Max. current of PV array:	17.3 A	8.7 A
Max. DC current:	18 A	10 A

Fig. 2. Compatibility of the electrical characteristics of our sizing.

3. PV Grid Connected System Model

The proposed grid-connected PV system is shown in Fig. 3; which is mainly consisted of a PV array, a grid-tie inverter. Solar radiation (G) and ambient temperature (T) are the main parameters that specify a PV module power production. A PV module power production has a direct proportion to the solar radiation. In the meanwhile, PV modules' current is increasing proportionally with the increase of solar radiation [16]. As for the PV modules' voltage, it decreases with the increase of module's cells temperature and this leads to a decrease in PV module production. Finally, it is worth telling that this is the first study that is done for the DEDUENERT Prototype based on experimental results whereas all of the previous studies were done based on simulation results. The inverter illustrated in Fig. 3, converts the DC power produced from the PV array to an AC power that is ready to be injected to the grid.

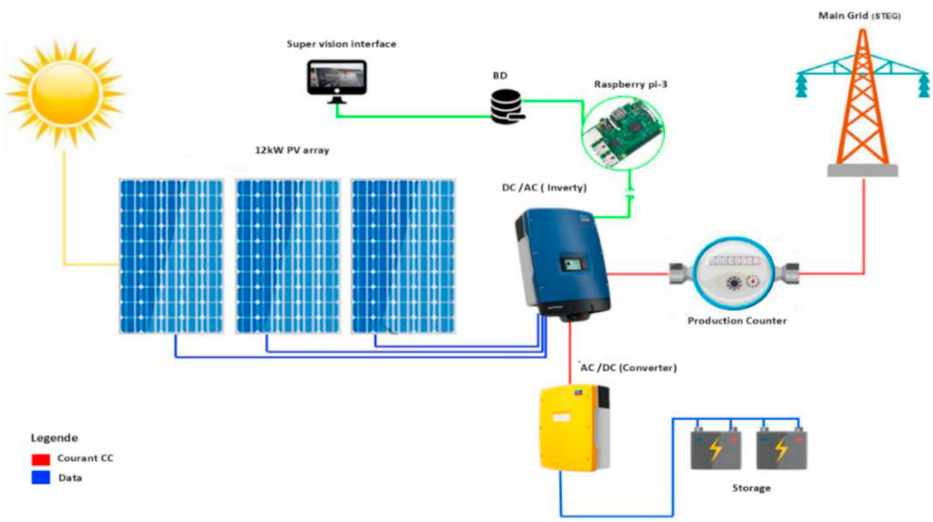
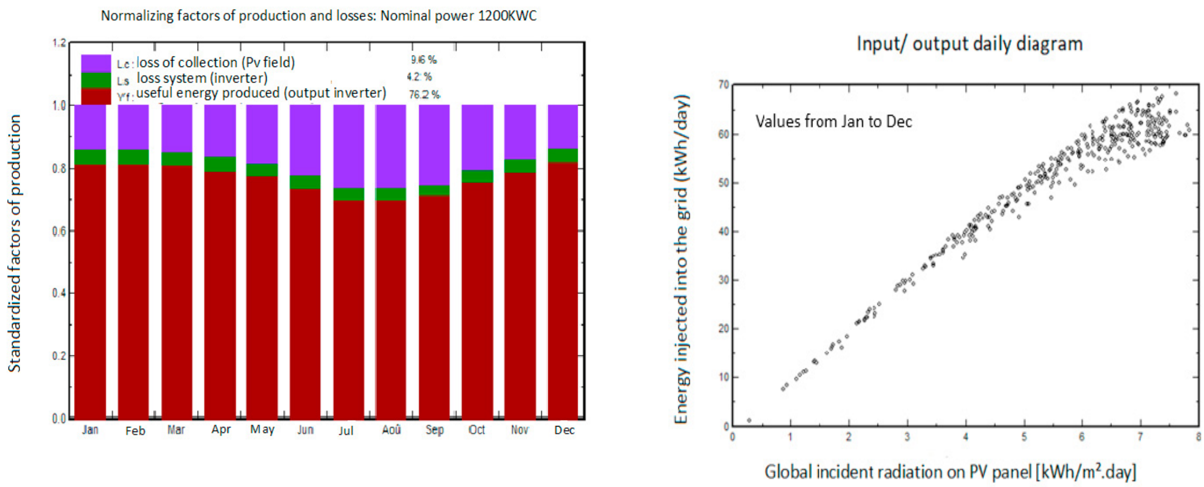


Fig. 3. Grid-connected PV system (Tunisian prototype).

3. 1. Proposed system implementation and simulation results

In this study, *PV*Sol* Software is used to simulate the proposed system first. This software is able to design and simulate PV grid connected system providing the optimum inverter size that perfectly matches the PV array capacity in order to achieve the maximum power conversion efficiency. Moreover, *PV*Syst* Software provides recommendation for the optimum monthly tilt angle that the PV array must be slanted in order to collect the maximum achievable solar energy yield [17]. In addition to that, *PV*Syst* Software provides a one-year simulation for the system indicating the power production, power losses, yield factor and capacity factor (Fig. 4*a*).

In order to investigate the feasibility of the proposed PV system, technical and economical evaluation criteria of the energy injected into the grid compared to the global incident radiation on PV panel are applied (Fig. 4*b*). In this study, two technical factors namely, capacity factor (CF) and yield factor (YF) are applied to evaluate the productivity of the proposed system. Meanwhile, the payback period (PBP) and the cost of energy (CoE) are used to assess the feasibility of the proposed system [18, 19]. In this research, *PV*Syst* Software as well is used as benchmark software in order to validate the results generated by the *PV*Sol* Software. Moreover, the experiment results are utilized to compare both software in terms of prediction accuracy.



(a) *(b)*

Fg. 4. Daily diagram, normalizing factors of production and losses

4. Results

4.1. Simulation by SMA Sunny Design and PV Sol Software

In the last study [13], we have realized a simple simulation for the Tunisian photovoltaic installation by the *SMA Sunny Design*, which is photovoltaic software for SMA inverters like our inverter. The important object for this sizing is to compare the results for the power, voltage and the current compatibility, which are found theoretically with those found by this software [14, 15].

Figure 5 presents the compatibility for the voltage range and the input current between the out photovoltaic field and the input of the inverter. The following figure 6 presents the consumption profile for our system by using some battery to storage some energy for lighting at night, and the effect of this installation to reduce the quantity of electricity purchased from the grid.

We know that the energy consumed by our laboratory per year is equal 49505 kWh and with results of this profile of self-consumption; we can conclude that the self-sufficiency quota is equal 32.2% (in percentage of PV Energy) and the self-consumption quota is equal 82.4% (in percentage of Energy Consumption per year).

On the other part, we have also realized a simulation for our photovoltaic installation by the *PV**Syst software to have some idea about the efficiency for this system and to compare some results with the previous results given by *SMA Sunny Design* software. We noted that by summing each monthly power produced by the Renewable Energy System RES (Fig. 6), we find a very similar value to that found by using the *SMA Sunny Design* software (Fig. 5). A slight difference between the two results is due mainly to the difference between the values of each weather databases [14, 15]. To validate The *PV*Syst* Software and show its superiority as compared to other software such as SMA software, the measured data of monthly production is compared with *PV*Syst* results as shown in Fig. 6. The next figures show a likely matching between the calculated values and measured profiles with variation that is less than 7%.

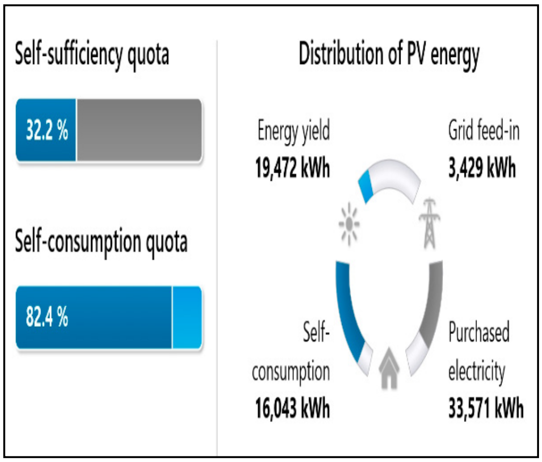


Fig. 5. Self-Consumption Profiles (Tunisian Prototype).

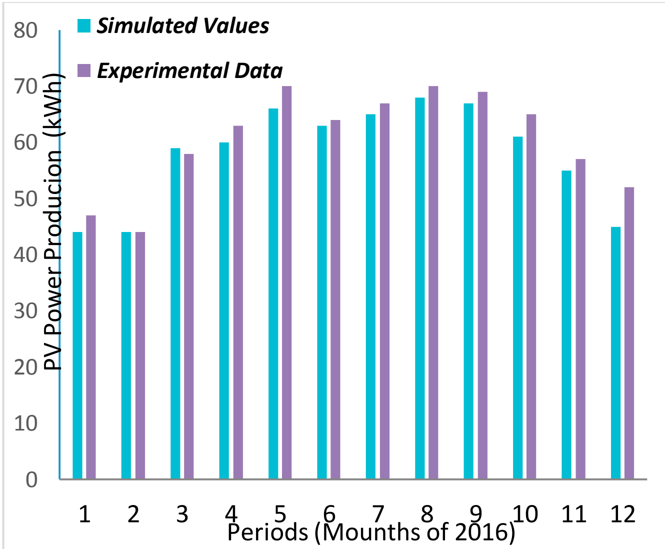


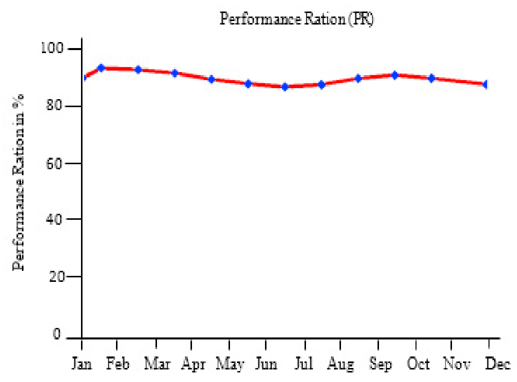
Fig. 6. Self-Monthly Production profiles

The performance ratio (PR) or Performance Factor is indicated in percentage and is the ratio between the real and the theoretical yield of the photovoltaic system. If the value of this ratio approaches of 100%, we consider that this photovoltaic system has an efficient operation. The performance ratio is calculated as follows:

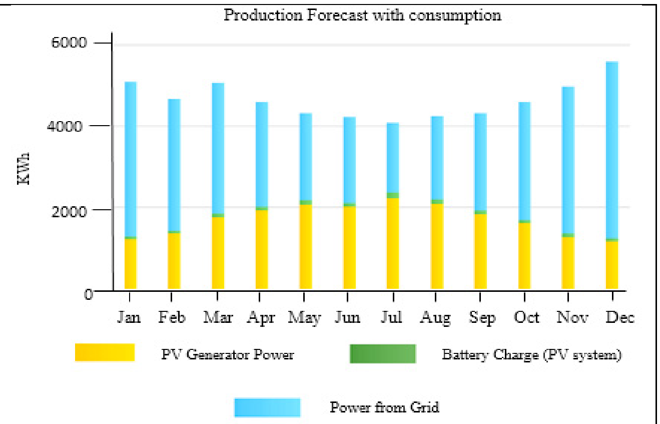
$$\text{Performance Ratio} = \text{Real yield} \Big/ \text{Theorical yield} \tag{4}$$

In the following figure 7, we present the profile of this performance ratio. We noted that our installation is effective because it have a higher performance ratio (more than 80%) and we deduct that this value is fluctuating because of some conditions such as panel temperature, shading, solar irradiation and the thermal and conduction energy losses.

In the following figure 8, we present the quantity of the energy produced by the PV installation of DE.DU.ENERT prototype, the energy consumed from the grid and a little quantity of energy stored by using batteries (Fig. 8). We noted that by summing each monthly power produced or purchased, we find a very similar value to that found previously by using the *SMA Sunny Design* software. This small variation is due to the difference between the values of each weather databases.



• Fig. 7. Performance ratio



• Fig. 8. Production forcast with consumption for Tunisian Prototype.

4.2. Experimental setup and results

From the previous figure, it is clear that the system generates good current during the day as compared to the actual one. Assume that a performance factor is defined as the actual performance of the PV system to the theoretical performance of the PV system, then, the performance factor of the proposed system is about 84.6%. The performance factor is somehow acceptable according to [18]. However, there are many reasons that may reduce the performance of PV system. First, the dust deposition is of the important factors that reduces the amount of the output current. In addition, the high cell temperature also reduces the performance of the PV system. As a fact, the cell temperature affects negatively the performance of the PV cell due to its proportional effect on the voltage and logarithmic effect on the current [18]. It has been proven that the performance factor was the lowest during the peak of the daily cell temperature profile [19]. This is to say, in order to achieve good performance factor, PV system cleaning and ventilating is very important in order to handle the dust deposition and the high cell temperature issues.
Figure 9 shows the total AC energy generated by the photovoltaic system of the PV array for two years 2016 and 2017. The PV field has been connected to the local electric grid in May 2016.

The AC power generated by the PV system during the first period of monitoring was 45637.65 kWh, with a monthly average power of 1485.23 kWh/month. The month with the greatest generation of energy was July, 2017 with 2022.204 kWh. According to the data logger acquisition, the average daily values of operating frequency and AC voltage over the period are 49.98 Hz (±0.02%) and 248.58 V (±0.21%), which comply with electricity regulation in the Tunisian electric grid.

The maximum efficiency of the generator took place in the month of June with a value of 14.5%, and the minimum efficiency occurred in the month of December with a value of 12.7%. These variations are due to the fact that the CRTEn is located in the region, characterized by intermittent atmospheric changes. The two diagrams in Figure 10 illustrate the amount of energy provided by the PV field. We are seeing a drop of production during the summer months, due in particular to the extreme rise in ambient temperature and the lack of technical maintenance of PV panels, inverters, and supervision devices of PV array.

At the end, and in line with Horizon 2020 objectives, the DE.DU.ENER.T. project provides:
• promotion and development RES-based DG;
• promotion and development of efficient energy use through actions aimed at reducing electricity consumptions and the development of near-zero energy buildings (NZEB), with significant effects on the whole electrical systems [20].

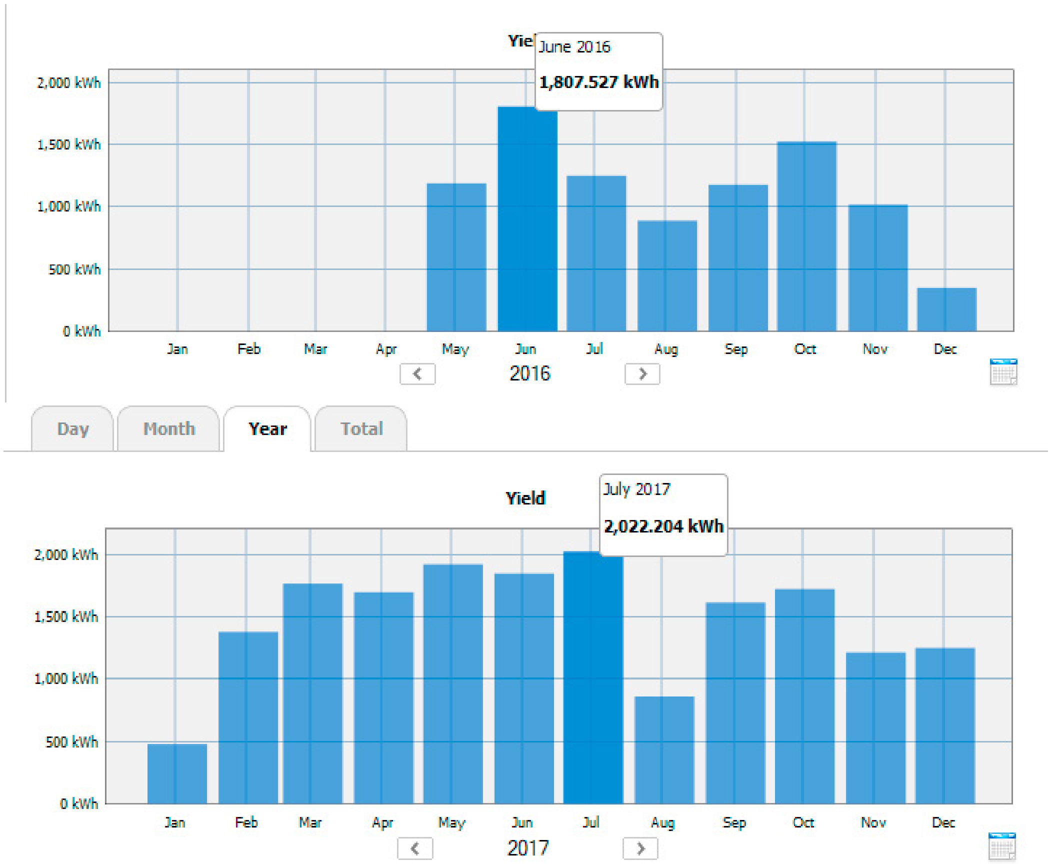


Fig. 9. Power production over two years 2016 and 2017.

5. Conclusion

In this study a 12 kW grid-connected PV system is designed, implemented and evaluated in The Research and Technology Centre of Energy CRTEn, Tunisia. Measured meteorological data for one year have been used in this study. This document is an evaluation for our DE.DU.ENER.T project funded in the framework of the trans-frontier cooperation program ENPI CT Italia-Tunisia 2007-2013. The block diagram illustrate perfectly the PV Plant structure and the life cycle of the PV instalation has been calculated and discussed.

Recent results of the simulation study realized by some industrial software such as *PV*Syst* and *PV*Sol* indicate that the hybrid electric system HRES could provide about 39% of the total consumption of the electricity for our laboratory. Our solar devices allow the order of 4500 KWh energy saving and CO_2 emissions reduction of about 2600 Kg per year.

In addition, the experimental results show that the performance factor of the proposed system is 84.6%. Meanwhile, the cost of the energy generated by the proposed system is 0.045 USD/kWh which means that the pay-back period is about 11 years. The conclusion from this study is that the price of energy generated by PV systems in Tunisia is lower than the subsidized price of energy generated by fossil fuel.

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