Influence of Battery Storage on Self-Consumption of Residential Photovoltaic Systems in a Mediterranean Climate

G. Mohand Kaci, A. Mahrane, K. Ghedamsi, M. Chikh

ABSTRACT--- Energy saving in homes can be reached thanks to optimized energy management. This paper deals with the case of a solar house, installed on the site of UDES in Bou-Ismaïl (Algeria) located in the south shore of the Mediterranean, which is used as a test bench for the developed energy supervision system. The house is powered by an on grid PV system with backup. The proposed supervision system looks for the optimal flow energy management taking into account the availability of the PV energy, the state of charge of the batteries and the energy demand of the loads while promoting the self-consumption and reducing the exchange of energy with the grid. The simulations of the monitoring system operation were carried out over a period of one year in order to match the energy demand with the local PV production using real daily consumption of the loads. It has been found that the storage improves significantly the local photovoltaic energy consumption by about 28% in winter, 95% in spring, 45% in summer and 42% in fall for the studied PV system (3.2kWp, 12kWh). This study has shown that there is a strong overall potential for improving self-consumption through the optimal management and storage of energy in the climatic conditions of northern Algeria.

Keywords— Self-consumption, Battery Storage, Energy management, Grid connected PV, load profile.

I. INTRODUCTION

In 2011, for the first time, 50 TWh of electrical energy was consumed by the residential sector in Algeria. In 2017 this consumption reached 61 TWh [1] with an average annual increase of 2.5% [2]. Moreover, economic and energy statistics show that electricity consumption in the residential and tertiary sector represents about 42% of the global Algerian electricity consumption [3]. Temporary deficit situations occur, especially during hot summer days that cause huge use of air conditioning. Continued growth in consumption is leading to challenges in the availability of electricity, and the residential sector appears to be the primary target for energy savings. In order to relieve the grid and to avoid electricity shedding, the integration of Renewable Energies (RE) to satisfy household electricity demand seems a promising option.

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G. Mohand Kaci, Laboratoire de Maitrise des Energies Renouvelables, Faculté de Technologie, Université de Bejaia, Bejaia 06000, Algérie. Unité de Développement des Equipements Solaires UDES, Centre de Développement des Energies Renouvelables /CDER , 42415. W.Tipaza, Algérie. (gh_mohandkaci@yahoo.fr)

A. Mahrane, Unité de Développement des Equipements Solaires UDES, Centre de Développement des Energies Renouvelables /CDER , 42415. W.Tipaza, Algérie.

K. Ghedamsi, Laboratoire de Maitrise des Energies Renouvelables, Faculté de Technologie, Université de Bejaia, Bejaia 06000, Algérie.

M. Chikh, Unité de Développement des Equipements Solaires UDES, Centre de Développement des Energies Renouvelables /CDER , 42415. W.Tipaza, Algérie.

In 2011, the government launched a national program for the development of Renewable Energies and Energy Efficiency. This program, which was updated in 2015, foresees the production of 22,000 MW for the needs of the national market over the 2015-2030 period. More than 4,500 MW will be installed by 2020. This program is mainly based on the photovoltaic (PV) (13,575 MW) and aims to achieve, by 2030, 27% of electricity production from renewable.

To get a good fit between photovoltaic energy production and energy this requires a storage system [4,5] or a DSM (Demand-Side Management) [6,7] or the combination of both solutions [8,9]. According to [10], storage allows both to manage the irregularity of PV production and increases self-consumption by about 31 to 34% compared to the PV system without backup.

In this article, an energy management strategy that has been developed is presented. It takes into account three requirements, (i) the PV energy produced is used to power the loads of the house, (ii) the battery is charged only by the excess PV energy, (iii) the battery discharges only to meet the energy demand of the loads. The objective is to estimate the potential for improving the PV self-consumption by using an energy management system in the solar home. The impacts and potential benefits of optimized energy management are evaluated in terms of (a) PV self-consumption, (b) the degree of the network independence, and (c) the peak clipping in load profiles of the house. The analysis is based on the use of a large number of actual meteorological data and load profiles synthesized from information on electricity consumption with a time resolution of 5mn for a whole year [11]. These data are used for the simulation of the photovoltaic system and the management of the energy monitoring system to determine the maximum potential for meeting the daily energy demand. The management strategy developed in this article meets the requirements initially set for both to increase the self-consumption and to reduce the injection into the network.

This article is structured as follows. Section 2 describes the house and provides a brief overview of the installed PV system. In section 3, the energy supervision architecture is described. The simulation results are presented in Section 4. Finally, section 5 concludes the article.

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II. CONFIGURATION OF THE SYSTEM

A. System description

The scheme of the proposed system is shown in FIG. 1. The topology of the selected system is based on an AC bus excluding any energy exchange between the storage system and the network [12]. The power generation system consists of a 3.2 kWp PV generator composed of monocrystalline silicon-based modules, inverters, a 12 kWh lead-acid battery bank, loads and a distribution network. Batteries are used to power the loads in the absence of PV production or grid failure [13]. In order to use the stored electricity, the home is equipped with a bidirectional battery inverter that also controls the energy flows in the house.

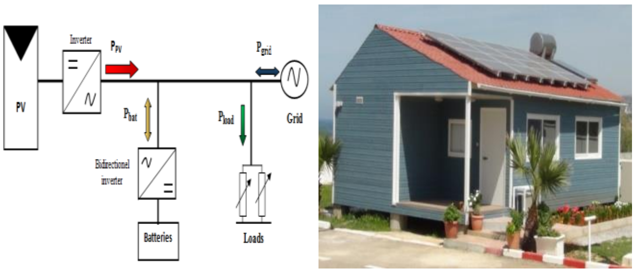

Fig. 1. (a) Topology of the PV system. (b) Overview of the solar house.

B. Input data

The simulation model uses as input data, for the supervisory system, the PV production data collected for one year from the PV plant. The values used for the household load profile are synthesized from the consumption profiles measured at a pace of 5 minutes from 78 typical households. In this study a daily consumption of 10.5 kWh was considered as energy demand of the home. Examples of consumption patterns for the four seasons of the year are shown in Figure 2. This home daily consumption profile corresponds to the all electric loads (air conditioner included) except those for space heating, hot water production and cooking that are using natural gas [14].

The daily consumption curve has four distinct parts that can be identified in figure 2 as follows:

- Low consumption during the night (1am to 4am) which varies between 0.3kWh and 0.5kWh for all seasons.
- An increase in consumption in the morning from 6am, due to the resumption of user activities.
- A decrease in consumption during the afternoons for all seasons except the summer season, this being mainly due to the rise in temperature. The average daily temperature recorded in the summer period is comprised between 38 ° C and 42 ° C [15].
- And finally, a peak consumption in the evening, around 8pm, which is mainly due to the massive use of home appliances, televisions, lighting etc.

C. PV System operation

The operation of the system could be described as follows: the power generated by the PV source is used primarily to satisfy the demand of the loads of the house. When the PV power is insufficient, the battery will be discharged. This functionality is limited by the sizing of the storage capacity [16]. In the afternoon, when the battery is fully charged, the PV energy must be injected directly into the network. Late in the night, when the battery is completely discharged, the electricity consumed will be supplied by the public network. The batteries are charged only by the PV generator according to the rules adopted for photovoltaic installations with backup connected to the network [17].

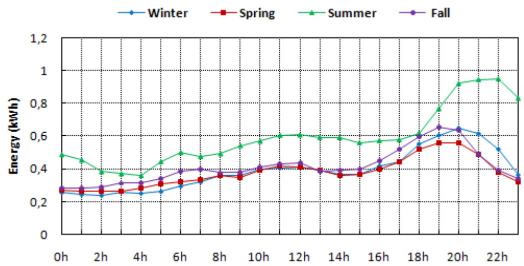

Fig. 2. Load curve of the solar house of a typical day for each season.

D. Objective

The main objective of the 'hybrid' PV-battery-network system is to meet the energy demand of the home by optimizing the use of PV electricity. To this aim, an energy management strategy has been adopted that takes into account the availability of PV energy, the load profile and the energy demand while controlling at each stage the charge and discharge of the batteries in order to maximize the self-consumption and reduce the amount of energy withdrawn from the network. The main aspect in this study is to determine the rate of self-consumption or in other words the self-consumed part in relation to the total PV production [18], which is defined as follows:

$$\text{Self-consumption} = \frac{\text{Self consumed energy PV}}{\text{Total PV energy produced}} \quad (1)$$

III. ENERGY MANAGEMENT SYSTEM

A. Energy distribution strategy

As mentioned above, the house is equipped with a lead battery bank with a voltage of 48 V and a capacity of about 12 kWh. In order to use the stored energy, the house is equipped with a bidirectional battery inverter. This inverter not only performs energy conversion, but also manages energy flows in the home in order to maximize the self-consumption, avoid the exchange of electricity with the grid and protect the batteries against overloads and deep discharges. The direction and state of the energy flows in the house are managed by the following equations:

- $P_L(t) < P_{PV}(t)$

If SOC<SOCmax ⟶ the surplus of the PV power produced is stored in the battery. P_{PV} is defined as the power provided by the PV and P_L as the power demand of the loads. Therefore, the power exchanged with the battery is defined by:

$$P_{bat}(t) = P_{PV}(t) - P_L(t) \quad (2)$$

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If SOC = SOCmax ⟶ the excess of PV power is injected into the network. In this case, the power exchanged with the network (grid) is defined as:

$$P_g(t) = P_{PV}(t) - P_L(t) \quad (3)$$

- $P_L(t) = P_{PV}(t)$

$$P_{bat}(t) = 0,\ P_g(t) = 0 \quad (4)$$

- $P_L(t) > P_{PV}(t)$

If SOC >SOCmin and $P_{bat} \geq |P_{PV}(t) - P_L(t)|$ ⟶ the battery is discharging. As a result, the power used to feed the load is defined as:

$$P_L(t) = P_{PV}(t) + \eta bat P_{bat}(t) \quad (5)$$

Where η is the coefficient of performance of the battery with a value of 0.8 for the system considered in this study.

If SOC =SOCmin ⟶ the power deficit is ensured by the network.

$$P_L(t) = P_{PV}(t) + P_g(t) \quad (6)$$

B. Evaluation method

The behavior of the supervision system is analyzed, over a period of 24 hours, trough two parameters (energy exchange , self-consumption) which are defined in the following.

The PV energy produced by the house is defined by:

$$E_{PV} = E_{PV,L} + E_{PV,bat} + E_{PV,g} \quad (7)$$

Where E_{PV} is the total amount of energy generated by the PV field, $E_{pv,L}$ is the PV energy used to power the loads of the house, $E_{PV,bat}$ is the PV energy stored in the battery and $E_{PV,g}$ is defined as the PV energy injected into the network.

The consumption of the loads is defined by:

$$E_L = E_{PV,L} + E_{g,L} + \eta bat E_{bat,L} \quad (8)$$

Where E_L is the total amount of energy used by the charges, $E_{g,L}$as the energy withdrawn from the network, $E_{bat,L}$ is the total amount of energy extracted from the battery.

On the basis of the above definitions, the self-consumption coefficient is defined by the following relation:

$$Self-consumption = \frac{E_{PV,L} + \eta bat E_{bat,L}}{E_{PV}} \quad (9)$$

IV. RESULTS OF ENERGY FLOW SIMULATION

The evaluation of the self-consumption of the solar house installed on the UDES site (Bou Ismaîl, Algeria), with and without storage has been done by using the case of one typical day. The simulations were performed using actual PV generation and load consumption data taken from an annual database measurement.

The energy flows present in the solar home are illustrated in Fig. 3 in the case of a PV system without storage (a) and with storage (b). For the PV system without storage, it could be noticed that the PV generation covers the energy demand of the house only between 06am and 1pm. Beyond 1pm, the power supply of the loads is ensured by the network. The daily energy balance for the chosen day shows that more than 50% of the PV production is injected into the grid and the average value of the self-consumption factor does not exceed 45%. For the PV system with a battery bank capacity of 12kWh, the energy produced during the low consumption hours are stored in the batteries and it is then used later when the demand exceeds the production. The storage allows both to maximize the self-consumption and reduce the amount of energy imported from the network. The Fig.3-b shows that at noon, the PV production is greater than the energy demand of the house which allows the batteries to charge, in order to be used to clip the peak of the morning (between 05am and 08am) and the evening peak (between 4pm and 11pm).

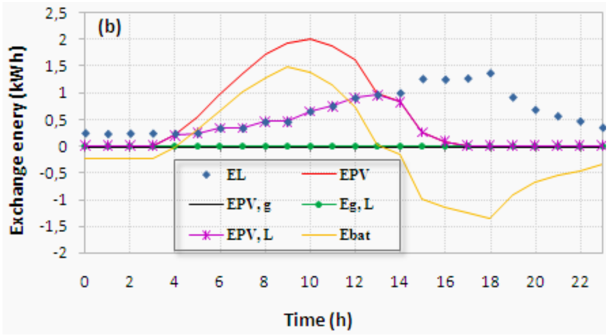

Fig. 3. Energy flow in the solar house for a typical summer day: (a) without storage and (b) with storage.

Figure 4 shows, for a given two consecutive days in July 2017, the effect of the combined action of storage and management strategy that have been implemented. It should be noted that for the two days considered, the PV generation is mainly concentrated between 6am and 7pm which allows the battery to be charged by the excess of the PV production. Later in the day, the battery is discharged to power the evening loads until all the stored PV electricity has been used.

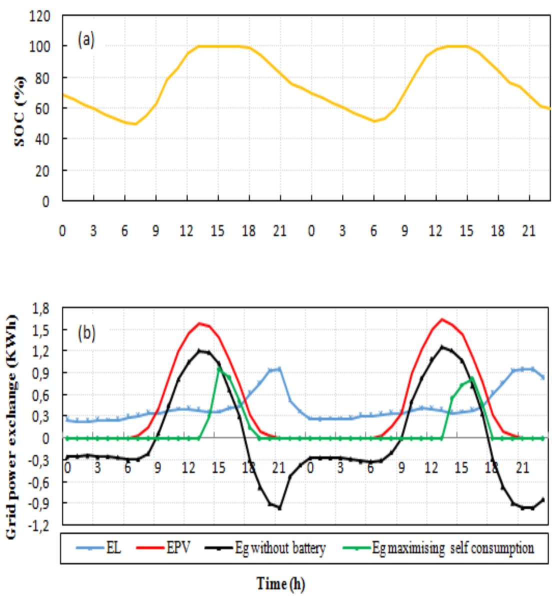

Fig. 4. (a) Battery State of charge and (b) Energy Management strategy effect on grid power exchange for two consecutive days.

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As it can be seen on the figure 4, for the case without battery, peak loads are provided by the network. Indeed, a large part of the PV production is injected directly into the network because the period of strong PV generation does not coincide with the peak consumption especially in the evening (between 5pm and 8pm). For the PV system with storage, for the two consecutive days considered it could be noticed that the battery discharge satisfies the high peak demand without withdrawal of electricity from the grid. After the peak demand, the photovoltaic electricity can again feed the loads directly and the battery is charged with the excess energy.

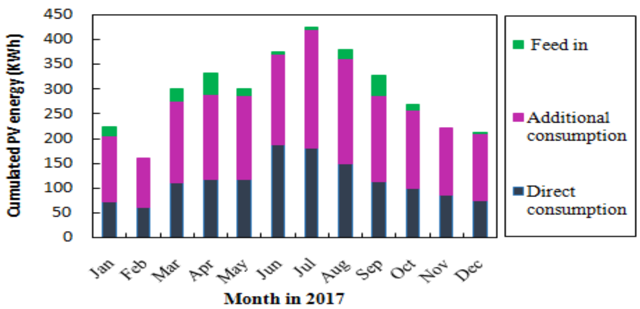

Fig.5. Monthly PV utilization rate when using the energy management proposed strategy to maximize the self-consumption.

The PV energy produced by the hybrid system (PV-battery-network) can be divided into three parts: a part for a direct local consumption, a part for an additional local consumption which depends on the installed battery capacity and the last part is the unused energy which is injected into the network. The results of the simulations (Figure 5) show that the percentage of PV energy consumption increases by using storage. This additional local consumption (indirect consumption through batteries) is greater than direct local consumption which achieves a maximum use of PV energy that exceeds 70% for all months of the year. The use of storage with an energy management strategy improves the PV self-consumption which can reach a rate of 98%.

A. Reduction of power exchange

Figure 6 shows quantitatively the influence of the storage on the energy exchange with the grid for a whole year. With a battery-free PV system, all excess power that is not self-consumed is injected into the grid. The use of a storage system reduces the injection into the network by storing the energy and supplying it later. The positive and negative values respectively represent the injected and withdrawn power. The strategy to maximize self-consumption is to store energy as soon as the excess power occurs. Therefore, this strategy relieves the network by reducing the high injection. As it can be seen in Figure 6, the PV system without storage shows significant positive values because the peak load demand is outside the period of high PV output.

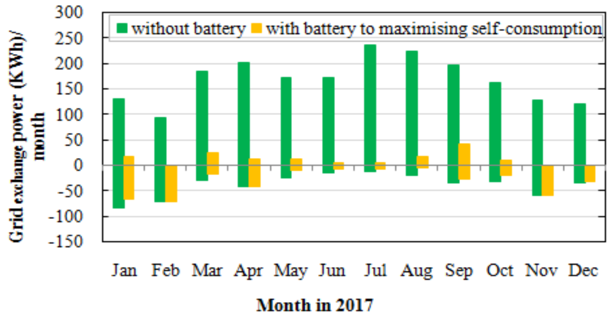

Fig.6. Monthly Energy exchanged between the grid and the PV system without a battery bank and with a battery bank.

The strategy adopted leads to a decrease of the amount of energy withdrawn from the network which is then less than 30% of the consumption of the loads, which represents around 3kWh /day throughout the year.

B. Self-consumption and energy balance

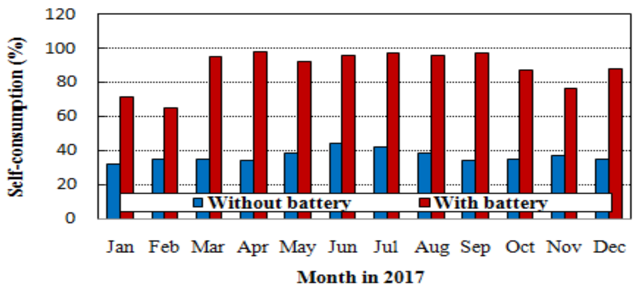

Fig.7. Monthly self-consumption rate of energy in the solar home for the year 2017.

In Figure 7, the monthly rate of self-consumption for the case with and without storage is indicated. The simulation results show that the storage has a very high effect on the rate of satisfaction of the energy demand of the house. The solar house's annual report shows that the loads consume more than 80% of the PV output, which means that the percentage of PV energy injected into the grid is lower. In this case, the self-consumption coefficient exceeds 90% for the spring and the summer. For winter and fall, the self-consumption rate varies between 64.9% and 87.9% despite a decrease in PV production. Using a storage management significantly improves the rate of satisfaction of the home energy demand so a rate of a self-consumption greater than 70% is reached for the majority of the days of the year.

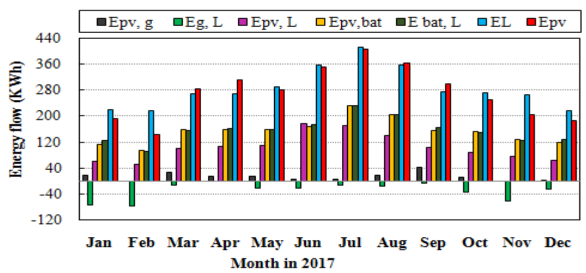

Fig. 8. Annual energy distribution in the solar home (2017).

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As mentioned above, the main objective of our work is to maximize the self-consumption by using as much as possible the PV energy produced. For most of the months of the year, the energy produced by the PV field is not sufficient to meet the home energy demand except for March, April, August and September. Figure 8 shows the annual simulation results obtained for the PV system with backup. The daily energy load demand varies between 7.5 and 9kWh for winter and fall, and between 11 and 13.5kWh/day for spring and summer. In addition, the amount of PV energy produced is higher in summer than in winter, the highest level of PV production is reached in July, the lowest in February.

The amount of the PV energy injected in the grid decreases by more than 50% for the whole year. In other words, the amount of electrical energy exchanged with the network for the PV system with the storage is around (2,5kWh/day) which is lower when compared to the case without storage (13.15kWh/day). The optimization of the energy storage system can significantly reduce the amount of energy injected in the grid and withdrawn from the grid. In addition, using the batteries increases the self-consumption and reduces the network solicitations.

V. CONCLUSION

In this paper, a method based on a storage system supervision to increase the self-consumption in a solar home equipped with on grid PV system was presented. A good energy management has not only led to a high rate of self-consumption, but also to a high degree of network relief.

The simulations were conducted for a home equipped with an on grid PV system with backup using real data (PV production and energy demand) for a year. It has been shown that using a storage management significantly improves the rate of satisfaction of the home energy demand and a self-consumption rate greater than 70% could be reached for the majority of the days of the year. On the other hand, the management strategy adopted have led to a decrease of the amount of energy withdrawn from the network which is less than 30% of the consumption of the loads, which represents around 3kWh /day throughout the year.

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