

ENERGY COST ANALYSIS OF STAND ALONE PHOTOVOLTAIC SYSTEMS

Salima KEBAILI¹, Hocine BENALLA²

¹Department of Science and Technology, Oum El Bouaghi University, Algeria.

²Department of Electrotechnics, Constantine1 University, Algeria

Abstract: System power reliability under varying weather conditions and the corresponding system cost are the two main concerns for designing stand alone photovoltaic systems (SAPV). An energy cost evaluation of a SAPV using sinusoidal profile is developed. This paper presents, for a first time, the more accurate mathematic models for characterizing PV module, battery and converters (DC/DC and DC/AC). Secondly, a methodology for studying the impact profile load parameters on the energy cost of an SAPV is proposed. Two cases are considered, unitary and constant efficiencies. The results obtained give the minimum energy cost and downsizing of the system during 30 years of the life cycle for each case.

Key words: SAPV system, Energy Cost, Load profile model, solar profile model, Modeling, Simulation.

1. Introduction

The rapid depletion of fossil fuel resources on a world-wide basis has necessitated an urgent search for alternative energy sources to cater to the present day demands. Alternative energy resources such as solar have attracted energy sectors to generate power on a large scale [1]. Due to the alternation of day and night and change of the weather, there exist instability shortcomings in electric energy production and the variation solar may not match with the time distribution of demand [2].

In stand alone system the solar energy yield is matched to the energy demand. Since the solar energy yield often does not coincide in time with the energy demand from the connected loads, additional storage systems (batteries) are generally used [3]. This SAPV system typically consists of a solar array, a controlled with maximum power point tracker (MPPT), a battery, an inverter and loads as illustrated in figure.1.

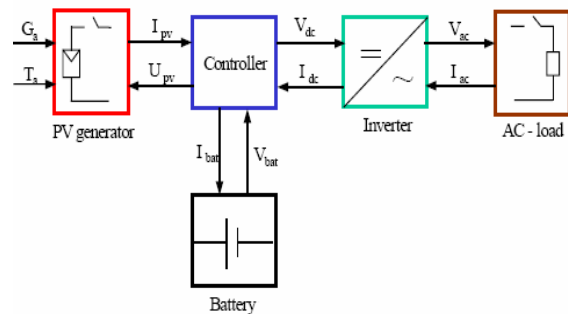


Fig.1. SAPV system proposed

For SAPV system application, storage cost still represents the major economic restraint. Increasing the correlation between the photovoltaic electricity production and the load profile is much a favourable option, primarily to reduce the energy cost associated with the storage system and hence the overall cost of the system.

In this paper, a mathematical model of each components of a SAPV system is proposed. This is followed by a description of the basic concepts related to the energy cost. The time horizon of 30 years is considered. Acting on the load profile shape reduces the energy cost on the life cycle of SAPV system. In this study, two cases are considered. Firstly, the different losses of SAPV system will be neglected. Secondly, the energy efficiencies will be constant. Finally, for each case, the results are discussed and compared based on energy cost of the system.

2. Mathematical model

SAPV systems consist of a PV array, battery bank, a controller with maximum MPPT, an inverter and loads.

2.1 Modeling of PV array

The performance of crystalline silicon PV module is a function of the physical variables of the PV cell material, the temperature of solar cells and the solar irradiance exposed on the solar cells [4]. In this paper, a polynomial model is used. The maximum power output of PV module is given by [5]:

$$P_{max} = \frac{G}{G_0} (P_{max0} + \mu_{pmax} \cdot (T_j - T_0)) \quad (1)$$

The junction temperature is defined as:

$$T_j = T_a + \frac{G}{800} (Noct - 20) \quad (2)$$

Where

G_0, G : Reference and given solar irradiances respectively, (W/m^2).

T_0, T_a, T_j : Reference, ambient and given junction temperatures respectively, (K).

P_{max0} : Maximum power in the standards conditions, (W).

μ_{pmax} : Temperature coefficient of power is equal to $-(0.5 \pm 0.05)\%/^{\circ}C$.

$Noct$: Normal operating cell temperature is range between $45-49^{\circ}C$.

2.2 Battery model

The battery bank, which usually of the lead acid type, is used to store surplus electrical energy, to regulate system voltage and to supply power to load in case of low solar conditions. Several factors that affect the battery behaviours have been taking into account, such as the charging efficiency, the self-discharge rate as well the battery capacity [1].

The battery is modelled by two electrical non linear elements: a voltage source (V_1) representing the open-circuit voltage of the accumulator and an internal resistance (R_1) for the different losses as illustrated in figure.2.

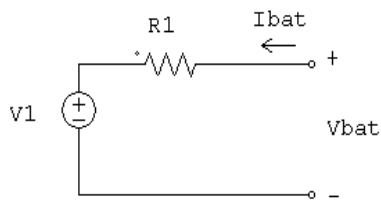


Fig.2. Battery model

The electrical equations of the accumulator voltage for charging and discharging are described below [6, 7]:

- Charge

$$V_1 = (2 + 0.148 \cdot SOC(t)) \cdot n_s \quad (3)$$

$$R_1 = \left(\frac{0.758 + \frac{0.1309}{n_s(1.06 - SOC(t))}}{SOC_m} \right) \quad (4)$$

- Discharge

$$V_1 = (1.926 + 0.124 \cdot SOC(t)) \cdot n_s \quad (5)$$

$$R_1 = \left(\frac{0.19 + \frac{0.1087}{n_s(SOC(t) - 0.14)}}{SOC_m} \right) \quad (6)$$

In this simplified study, in order to prevent over-discharge and to limit gassing process, the state of charge (SOC) is held in a limited range [8]:

$$SOC_{min} \leq SOC \leq SOC_m \quad (7)$$

2.3 Inverter

The inverter modelling is based on the energy efficiency curve. This inverter model has been deduced from the normalized of the efficiency curve of a rated power inverter. The efficiency expression is given by [5,9]:

$$\eta = \frac{\frac{P_s}{P_{nom}}}{\frac{P_s}{P_{nom}} + n_0 + m \left(\frac{P_s}{P_{nom}} \right)^2} \quad (8)$$

With ,

$$n_0 = \frac{1}{99} \left(\frac{10}{\eta_{10}} - \frac{1}{\eta_{100}} - 9 \right) \quad (9)$$

$$m = \frac{1}{\eta_{100}} - n_0 - 1 \quad (10)$$

The η_{10} and η_{100} are the efficiencies at 10% and 100% of rated power.

We can also apply the same model for the DC/DC Cuk model converter maximum power tracker MPPT. The figure .3 shows the efficiencies curve of inverter and DC/DC Cuk converter.

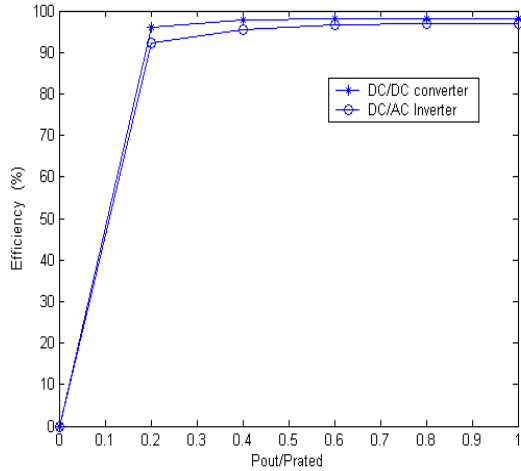


Fig.3. Simulated energy efficiencies of different converters.

3. Energy Cost of SAPV system

Our study based on mono-objective optimization concerns the energy cost of the entire SAPV system during the 30 years life cycle under an assumption that the loss of load probability is negligible. The four optimization variables are:

- The PV peak power, P_{pv}
- The power of DC/DC converter, $P_{DC/DC}$
- The apparent power of the inverter, S_{ond}
- The storage capacity of battery, E_{bat}

The energy cost (kWh) of each element depends on element technologies and the life cycle assumption. Therefore, the energy cost of a SAPV system can be expressed as follows [9]:

$$C_{Total} = C_{PV} \cdot P_{pv} + C_{bat} \cdot E_{bat} \cdot n_{bat} + C_{ond} \cdot S_{ond} \cdot n_{ond} + C_{DC/DC} \cdot P_{C/DC} \cdot n_{DC/DC} \quad (11)$$

Where,

n_{bat} , n_{ond} and $n_{DC/DC}$ are the numbers of lead-acid battery, inverter and DC/DC converter replacements respectively.

C_{pv} , C_{bat} , C_{ond} and $C_{DC/DC}$: are energy costs of PV panels, battery, inverter and DC/DC converter respectively.

E_{bat} : is the battery capacity

Table.1 summarizes the energy costs and life cycle assumptions of the different components of a SAPV system.

Components	Energy cost	Life cycle (years)
PV module	9 kWh/W _c	30
Battery	359 kWh/kWh	5
DC/DC converter	0.3kWh/W	10
Inverter	0.3kWh/VA	10

Table.1. Energy costs and lifetime of the system components.

4. Load profile model

In this section, the aim is to study the impact of the different parameters of the load profile, using idealized sinusoidal load and solar profiles, on SAPV system energy cost. We can assume that the daily consumed energy is equal to the produced energy.

The load profile model is given by [10]:

$$P_L(t) = P_{L-moy} (1 + r \cdot \cos(\omega t - \Delta\theta)) \quad (12)$$

The production profile is expressed by:

$$P_{pv}(t) = P_{L-moy} (1 - \cos \omega t) \quad (13)$$

Where,

P_{L-moy} : is the average power load, (W)

r : Relative amplitude

$\Delta\theta$: Phase difference, (rad)

The two modifications parameters are relative amplitude and phase difference.

In this study, two cases are considered.

4.1 Unitary efficiencies

No losses in the battery, DC/DC converter and inverter. The installed PV peak power and the power of DC/DC converter are twice the average consumption power. The inverter must be sized at least for the load profile maximum power. So, it's depending on the relative amplitude of the load profile as follows:

$$S_{ond} = (1 + r) \cdot P_{L-moy} \quad (14)$$

Lastly, the expression of the storage capacity of battery is:

$$E_{bat} = \int_0^{t_1} (r \cdot \cos(\omega t - \Delta\theta) - \cos(\omega t)) dt + \int_{t_2}^T (r \cdot \cos(\omega t - \Delta\theta) - \cos(\omega t)) dt \quad (15)$$

With,

$$t_1 = \frac{T}{2} \left(1 - \frac{1}{\pi} \arctan\left(\frac{1+r \cdot \cos(\Delta\theta)}{r \cdot \sin(\Delta\theta)}\right)\right) \quad (16)$$

$$t_2 = t_1 + \frac{T}{2} \quad (17)$$

According to equation (11), the energy cost of SAPV system is:

$$C_{Total} = P_{L-moy} (2 \cdot C_{pv} + 2 \cdot n_{DC/DC} C_{DC/DC} + n_{ond} \cdot C_{ond} (1+r) + n_{bat} C_{bat} \cdot E_{bat}) \quad (18)$$

The optimal sizing of SAPV system corresponds to a load profile exactly equal to production profile. So, the need of battery is ignored and the downsizing of the system is achieved. Therefore, the optimal energy cost can be given by:

$$C_{Total_{opt}} = 2 \cdot P_{L-moy} (C_{pv} + n_{DC/DC} \cdot C_{DC/DC} + n_{ond} \cdot C_{ond}) \quad (19)$$

4.2 Constant efficiencies

In reality, the losses in SAPV are far from negligible. Its have an influence on the system sizing. The DC/DC Cuk converter and inverter sizing are recalculated taking into account the energy efficiency:

$$P_{DC/DC} = \frac{P_{pv}}{\eta_{DC/DC}} \quad (20)$$

$$S_{ond} = \frac{(1+r) \cdot P_{L-moy}}{\eta_{ond}} \quad (21)$$

Considering sinusoidal solar profile, the new PV peak power is expressed as:

$$P_{pv} = 2 \frac{(P_{L-moy} \cdot T - E_{bat}) + E_{bat} / \eta_{ch} \eta_{disch}}{\eta_{DC/DC} \cdot \eta_{ond} \cdot T} \quad (22)$$

Where,

η_{ch}, η_{disch} : are charging and discharging efficiencies for the battery. A same value of 80% is considered.

5. Simulation results

The first step to size the source and the others devices is to evaluate the load profile. A family load profile is obtained by varying the two parameters characterizing this profile. The two modifications parameters are the relative amplitude and phase difference.

The load average power is 1000W which correspond to a 109500 kWh electrical energy total amount within a 30 years lifetime.

Considering unitary energy efficiencies case, the total energy cost of SAPV system as illustrated in figure.4 shows that the optimal energy cost is reached while the load and solar profiles are similar ($r=1, \Delta\theta=\pi$). Its value is 21600kWh. The ratio between this quantity and the total electrical energy consumption during 30 years is about 18% only. On the contrary, the maximum of the total energy cost of SAPV system is obtained while the two profiles are in phase opposition ($r=1, \Delta\theta=0$).

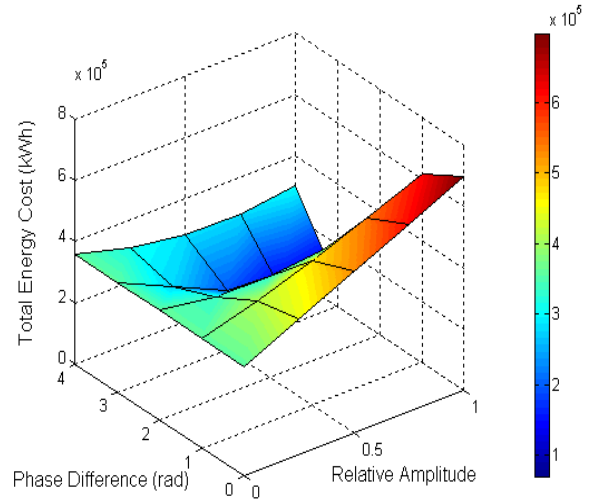


Fig.4. Total energy cost of SAPV system in unitary efficiencies.

Figure.5 illustrated the influence of the relative amplitude and phase difference on the energy cost of battery. We can see that this energy cost is zero when ($r=1, \Delta\theta=\pi$). So, while the two profiles are in phase, the need of battery is ignored and hence the downsizing of SAPV system is reached. On the contrary, in phase opposition profiles ($r=1, \Delta\theta=0$) correspond to the higher of the energy cost of battery.

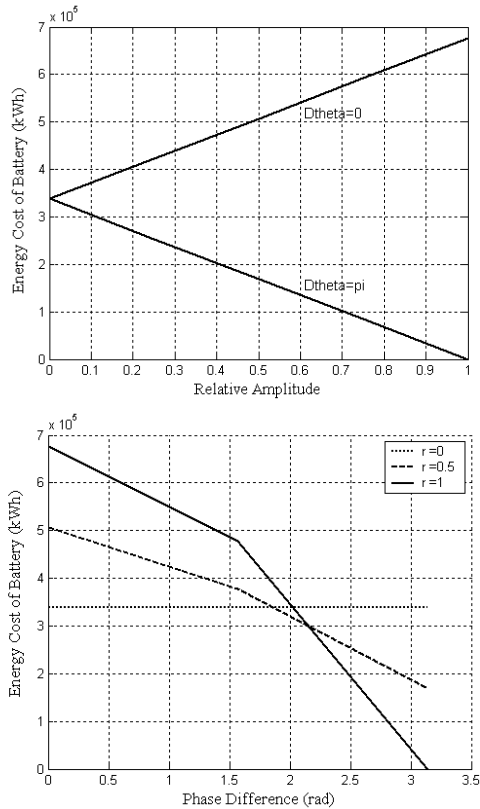


Fig.5. Impact of load profile on the energy cost of battery.

The energy cost of different components (inverter, battery, PV module and DC/DC converter) of SAPV system is shown in figure.6. The energy cost of inverter and battery are depending in the two modifications parameters of load profile. The PV module and DC/DC converter energy costs are constant under varying parameters of load profile. We can observe that, the PV module and DC/DC converter have a weakly energy costs but the highest energy cost is due to energy cost of battery.

In the constant energy efficiencies, the total energy cost of SAPV system is given by figure.7.

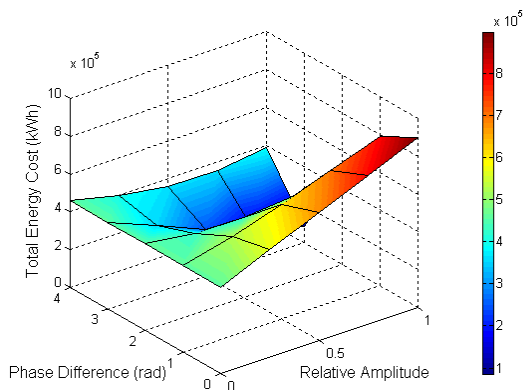


Fig.7. Total energy cost of SAPV system in constant energy efficiencies

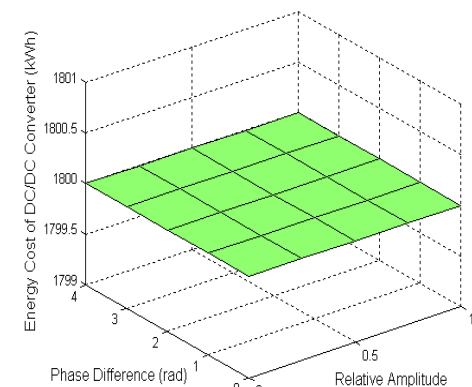
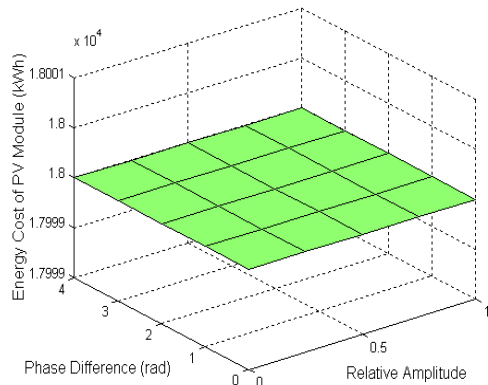
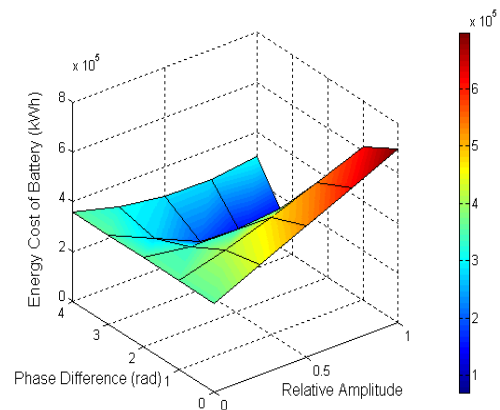
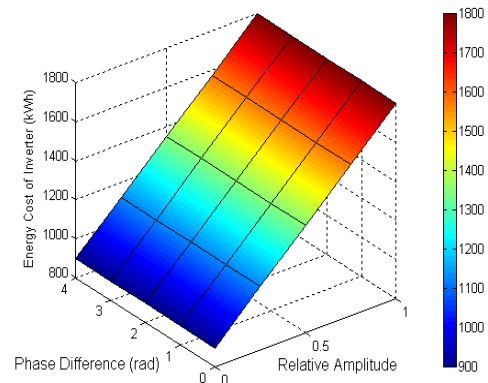


Fig.6. Energy cost of each components of SAPV system in unitary energy efficiencies

According to the figure.7, the optimal energy cost of SAPV system is about 26222 kWh while the load and solar profiles are similar ($r=1, \Delta\theta=\pi$). In the constant energy efficiencies, the total energy cost is higher than in unitary energy efficiencies because taking into account the losses in the different components allows the over cost of a SAPV system as shown in figure.8.

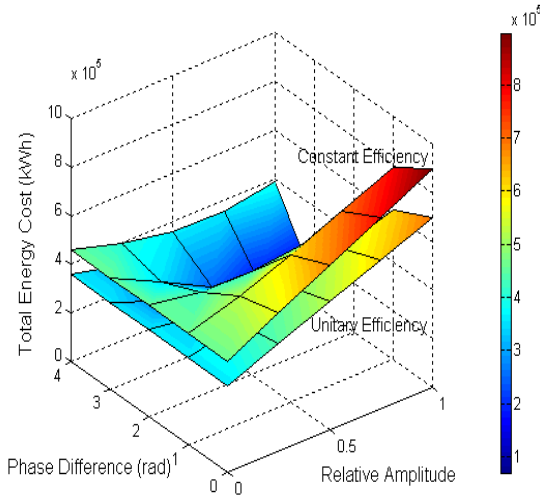


Fig.8 Total energy cost of SAPV in unitary and constant efficiencies.

Figure.9 shows the energy cost of different components (inverter, battery, PV module and DC/DC converter) of SAPV system in constant energy efficiencies. On the contrary of unitary energy efficiencies, the figures show the impact of the load profile parameters on the PV module and hence on the DC/DC converter.

6. Conclusion

In this paper, the life time of SAPV system is assumed to be 30 years. We presented the impact of load profile parameters on the energy cost of a SAPV system. Idealized sinusoidal solar and load profiles are used. The results show that while the load and solar profiles are in phase is equivalent to minimizing the energy cost of a SAPV system notably by avoiding the usage of battery.

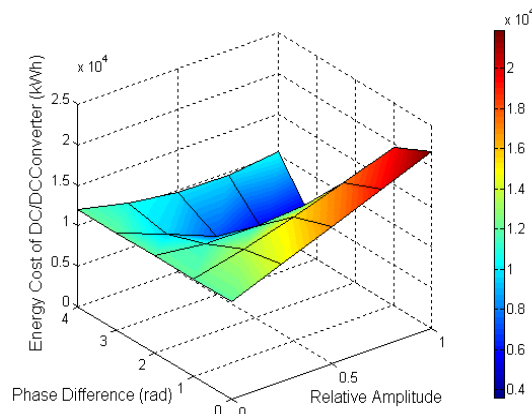
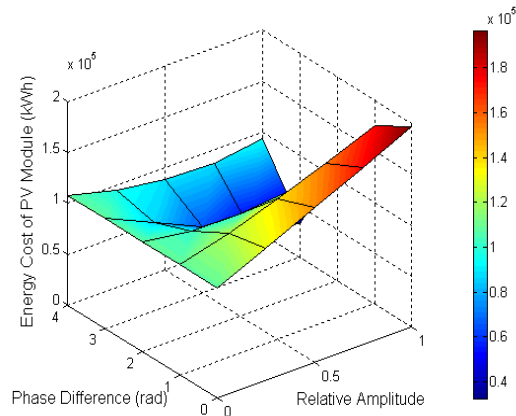
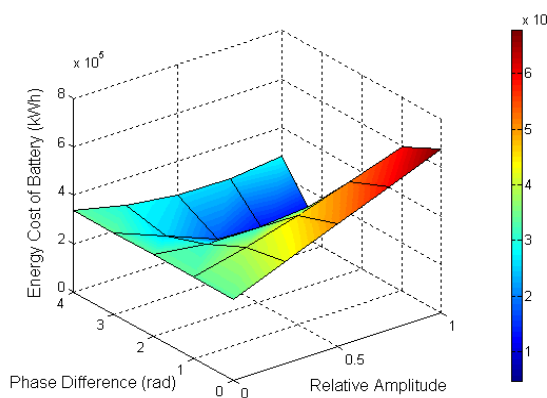
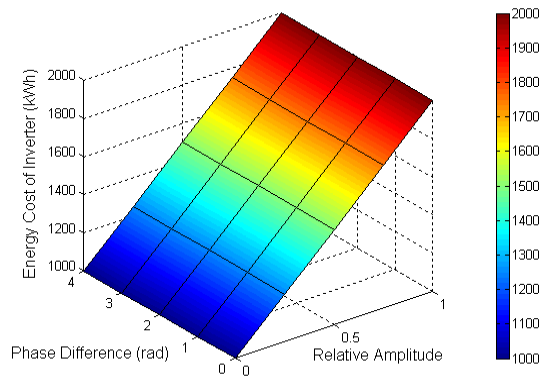


Fig.9. Energy cost of each components of SAPV system in constant energy efficiencies

References

1. Hongxing Yang, Wei Zhou, Lin Lu, Zhaohong Fang, 'Optimal Sizing Method for Stand Alone Hybrid Solar-Wind System with LPSP Technology by Using Genetic Algorithm', In: Solar Energy, (2008), Vol.82, p.354-367.
2. B.Ai, H. Yang, H.Shen, X.Liao, 'Computer Aided Design of PV/Wind Hybrid System', In: Renewable Energy, (2003), Vol.28, p.1491-1512.
3. Mahendra Lalwani, D.P.Khotari, Mool Singh, 'Size Optimization of Stand Alone Photovoltaic System under Local Weather Conditions in India', In: International Journal of Applied Engineering Research, Dindigul, (2011), Vol.1, N^o4, p.951-961.
4. Hongxing Yang, Wei Zhou, Lin Lu, 'A Novel Optimization Sizing Model for Hybrid Solar-Wind Power Generation System', In: Solar Energy, (2007), Vol.81, p.76-84.
5. Julien Labbé, 'L'hydrogène Electrolytique comme moyen de Stockage d'Electricité pour Systèmes Photovoltaïques Isolés', In : Thèse de l'Ecole des Mines de Paris, CEP, Sophia Antipolis, Décembre 2006.
6. S.Kebaili, A. Betka, 'Design and Simulation of Stand Alone Photovoltaic Systems', In: WSEAS Transaction on Power Systems, (2011), Issue4, Vol.6, p.89-99.
7. S.Kebaili, A.Betka, 'Efficient Lead Acid Battery Model in a Stand Alone Photovoltaic System', In: Conference International on Renewable Energy Approaches for Desert Regions and Exhibition, (2011), Amman, Jordan, April 26th – 28th
8. Abderrazak Hammouch, Marc Thele, Drik Uwer Sauer, 'Analysis of gassing processes in a VRLA/spiral wound battery', In: Journal of Power Sources, (2006), Vol.158, p.987-990.
9. Oliver Gercaud, 'Modélisation énergétique et optimisation économique d'un système de production éolien et photovoltaïque couplé au réseau et associé à un accumulateur', In : Thèse de l'Ecole Normale Supérieure de Cachan, Systèmes et Applications des Technologies de l'Information et de l'Energie, (2002), Antenne de Bretagne.
10. Y.Thiaux, J.Seigneurbieux, B.Multon, H.Ben.Ahmed, 'Load Profile Impact on the Gross Energy Requirement of Stand Alone Photovoltaic Systems', In: Renewable Energy, (2010), Vol.35, p.602-613.