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FEASIBILITY STUDY OF HYBRIDATION OF MINI DIESEL POWER STATIONS WITH PHOTOVOLTAIC ENERGY SYSTEMS

Said Diaf and Gilles Notton

ИЗСЛЕДВАНЕ НА РЕАЛИЗИРУЕМОСТТА ЗА ХИБРИДИЗАЦИЯ НА МАЛКА ДИЗЕЛОВА ЕЛЕКТРОСТАНЦИЯ И ФОТОВОЛТАИЧНА ЕНЕРГИЙНА СИСТЕМА

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Abstract:. Nowadays, the majority of diesel power stations located in the southern part of Algeria operate under difficult conditions and their diesel generators don't operate at nominal regime. The hybridation of micro diesel power stations with photovoltaic(PV) energy system permits to reduce the operation time of diesel generators and consequently reduces the fuel consumption. This paper presents a technical economic of hybrid photovoltaic–diesel–battery system. The objective of this work consists on developing a decision-making tool that allows the opportunity evaluation for combining micro diesel power stations with PV energy system.

This decision making tool is based on

- establishing of technical and economic models of the system's components
- optimization of system sizing

The simulation results related to this study will be presented and analyzed in this paper.

Keywords: hybrid system, diesel generator, optimum system sizing, loss of power load probability, levelized cost of energy

1. INTRODUCTION

Nowadays, the majority of diesel power stations located in the southern part of Algeria operate under difficult conditions and their diesel generators don't operate at nominal regime. This involves high fuel consumption and exorbitant maintenance cost. Also, the fuel transportation cost for long distance increases the total cost and consequently the kWh cost will be very high. The renewable energy systems with storage battery used for the electricity production are appropriate for the energy needs of small autonomous units. However, in order to offer a high reliability of power supply, the photovoltaic generator and battery bank must be sized large enough. Consequently, the investment costs become very high and the utilization of such system isn't economical.

The hybridation of diesel power stations with photovoltaic energy systems can offer the best solution for. This study investigates the feasibility of utilizing PV energy to meet the load requirements of the remote consumers in conjuncture with the diesel generator. The merit of hybrid PV-diesel battery system has been evaluated with regards to its size.

This paper is organized as follows: At first, a description of the studied system is presented, then the modelling of different system components are given in the second section. The system sizing and economic analysis are given in the third section. At last, the simulation results and conclusions are presented.

2. SYSTEM DESCRIPTION AND SPECIFICATION

The hybrid PV/diesel system consists of five main components which include a photovoltaic generator, batteries storage and power conditioning units (converters) and diesel generator as shown in Fig. 1. Table 1 shows the descriptions of the selected components.

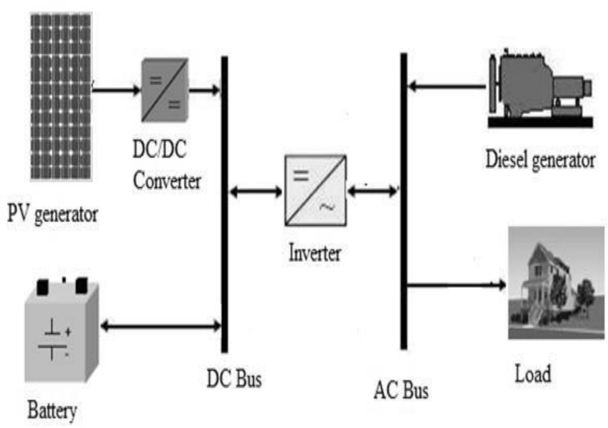

Fig. 1. Block diagram of the proposed hybrid PV/Diesel with battery energy system

3. MODELLING OF HYBRID SYSTEM

For a hybrid PV/diesel with battery storage, as shown in Fig. 1. three principal subsystems are included; the PV generator; the diesel generator and the battery storage. The different modelling steps are summarized in the following sections.

3.1 Photovoltaic generator modelling

The solar energy available on the titled plane is used for estimating the amount of electrical energy that can be generated using a PV module.
Assuming that maximum power point tracker (MPPT) is used and the PV module is always working at the maximum power point, the maximum output power of the PV module. P_{mp}. is calculated using the specification of the PV module under Standard Test Conditions (STC. cell temperature. T_{cref} =25°C. and solar irradiance . G_{ref} = 1000 W/m^2) provided by the manufacturer. as well as the ambient temperature and irradiation conditions. It can be given by the following equation:

(1) $$P_{mp} = I_{mp}\, V_{mp}$$

I_{mp} and V_{mp} are the optimum operating point current and voltage under arbitrary conditions and are defined as follows [1-5]:

(2) $$I_{mp} = I_{sc,ref}\left\{1 - C_1\left[exp\left(\frac{V_{mp}}{C_2\, V_{oc,ref}}\right) - 1\right]\right\} + \Delta I$$

(3) $$V_{mp} = V_{max,ref}\left\{1 + 0.0539\, log\left(\frac{G_t}{G_{ref}}\right)\right\} + \mu_{Voc}\, \Delta T$$

where

(4) $$C_1 = \left(1 - \frac{I_{max,ref}}{I_{sc,ref}}\right) exp\left(\frac{-V_{max,ref}}{C_2\, V_{oc,ref}}\right)$$

(5) $$C_2 = \frac{(V_{max,ref}/V_{oc,ref}) - 1}{ln\left(1 - (I_{max,ref}/I_{sc,ref}\right)}$$

(6) $$\Delta I = \mu_{Isc}\left(\frac{G_t}{G_{ref}}\right)\Delta T + \left(\frac{G_t}{G_{ref}} - 1\right) I_{sc,ref}$$

(7) $$\Delta T = T_c - T_{c,ref}$$

$V_{oc,ref}$ is the module open-circuit voltage under STC. $I_{sc,ref}$ is the module open-circuit voltage under STC. G_t is the global irradiance incident on the titled plane. T_c is the cell temperature and μ_{Isc} . μ_{Voc} are the current temperature coefficient of the PV module and the voltage temperature coefficient of the PV module respectively.

C_1 and C_2 are constants that depend on characteristics parameters of PV module and can be calculated as follows:

(8) $$C_1 = \left(1 - \frac{I_{max,ref}}{I_{sc,ref}}\right) exp\left(\frac{-V_{max,ref}}{C_2\, V_{oc,ref}}\right)$$

(9) $$C_2 = \frac{(V_{max,ref}/V_{oc,ref}) - 1}{ln\left(1 - (I_{max,ref}/I_{sc,ref}\right)}$$

ΔT and ΔI are given by the following equations

(10) $$\Delta I = \mu_{Isc}\left(\frac{G_t}{G_{ref}}\right)\Delta T + \left(\frac{G_t}{G_{ref}} - 1\right) I_{sc,ref}$$

(11) $$\Delta T = T_c - T_{c,ref}$$

The cell temperature influences the I-V characteristics and consequently the electrical efficiency of the PV module. The most common manner to determine the cell temperature T_c consists in using the Normal Operating Cell Temperature (*NOCT).* The value of this parameter is given by the PV module manufacturer. T_c is then dependent on the ambient temperature T_a and on the solar radiation G_t according to the following equation.

(12) $$T_c = T_a + (NOCT - 20)\frac{G_t}{800}$$

3.2 Battery modelling

The battery bank is one of the most important components of a stand-alone system. The charge state of battery at any time t is related to the previous charge state at the time t-1 and energy production and consumption situation of the system during the time from t-1 to t.

Two modes can define the battery operating: the charging and discharging process. The capacity of battery bank at the time t can be described as follows:

For the charging process, two cases can be presented:

When the diesel generator is running, the battery capacity is given by the following equation [5]:

(13) $$\begin{aligned} C_{bat}(t) &= C_{bat}(t-1) \\ &+ \left(P_{pvs}(t) + \left(P_{dg}(t) - P_{load}(t)\right)\eta_{conv}\right)\eta_{cha}\,\Delta t \end{aligned}$$

In case that the diesel generator doesn't run the battery capacity can be defined as:

(14) $$\begin{aligned} C_{bat}(t) &= C_{bat}(t-1) \\ &+ \left((P_{pvs}(t) - (P_{load}(t)/\eta_{conv})\right)\eta_{cha}\,\Delta t \end{aligned}$$

where $C_{bat}(t)$ and $C_{bat}(t-1)$ are the available battery capacity stored in battery bank at the time t and t-1. respectively. $P_{pvs}(t)$ is the output power of the PV generator. $P_{dg}(t)$ is the diesel generator power. $P_{load}(t)$ is the power consumed by the load at time t. Δt is the simulation time step. η_{conv} and η_{cha} are the bi-directional DC/AC converter efficiency and the battery charging efficiency respectively.
During the discharge process (when the diesel generator is off line and the power generated by the PV generator cannot meet the load demand) the battery starts to discharge according to the following expression [5]:

$$C_{bat}(t) = C_{bat}(t-1) + \left(P_{pvs}(t) - (P_{load}(t)/\eta_{conv})\right)\Delta t/\eta_{dech} \quad (15)$$

where η_{dech} is the battery discharging efficiency. At any time, the energy stored in batteries is subject to the following constraints (meets the following conditions):

$$C_{bat\,min} \le C_{bat}(t) \le C_{bat\,max}. \quad (16)$$

where C_{batmax} and C_{batmin} are the maximum and minimum battery capacity respectively.

3.3 Diesel generator modelling

A major characteristic of the diesel generator is its fuel consumption as a function of the output power. In many previous works presented in the literature, the fuel consumption of the diesel generator is assumed to be linearly increasing with the load [5, 6]. The linear relationship can be a good approximation of real diesel fuel curves (fuel consumption and output power).

In this study, the characteristic fuel consumption-output power of diesel generator is given in Fig. 2. The curve of Fig. 2 shows the fuel consumption curve of the 404C-22G diesel engine (power rating 18.5 kW) of PERKIN CONSTRUCTEUR as a function of its power

$$Cons_{fuel} = f(P_{ge}) \quad (17)$$

where $Cons_{fuel}$ is the fuel consumption in [l/h] and P_{ge} is the generated auxiliarly power

The data are obtained from the diesel generator manufacturers.

4. OPERATING STRATEGY

The architecture of hybrid PV-diesel-battery system is shown in Fig.1. The operation strategy is presented as follows:

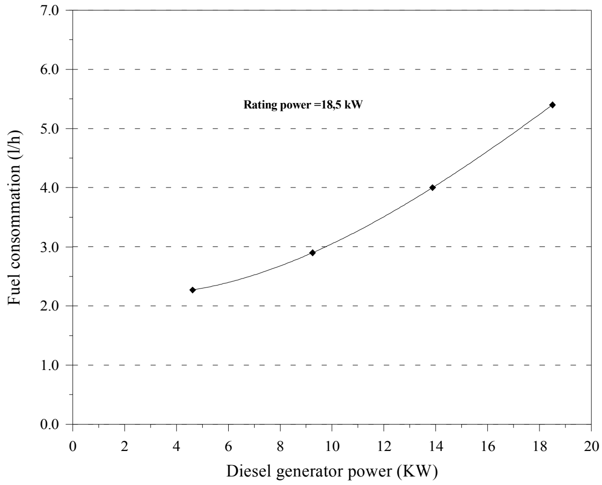

Fig. 2. Fuel consumption curve of the 404C-22G diesel generator (18.5 kW) [7]

- During this operation of the hybrid PV/wind system, different situations may appear
- In normal operation, the PV generator feeds the load demand. The excess energy from PV generator, if any, is stored in the battery until full capacity of the storage system is reached.
- In the event, that the output from PV generator exceeds the load demand and the battery's state of charge is maximum. then the excess energy is fed to some dump load or goes unused.
- In the worst case, if PV energy is not enough to meet the demand, the battery will discharge to cover the energy deficit.
- The diesel generator will only operate if the PV energy production fails to satisfy the load demand and when the battery's state of charge is minimum. If the diesel generator output power exceeds the load, the excess energy will be used to recharge the battery bank demand. In this case the PV production is used to recharge the battery bank with the excess energy produced by the diesel generator.
- The diesel generator will continue running until full capacity of the storage batteries is reached.

5. SYSTEM SIZING

Sizing is one of the most important tasks during the design of a stand-alone renewable energy systems. The sizing procedure will determine the power rating of each system's components needed to power the required load. The merit of a stand alone renewable energy systems should be judged in terms of the reliability of the electricity supply to the load. This usually quantified by the concept of the Loss of Power Supply Probability (LPSP). defined as the ratio of all energy deficits to the total load demand during the considered period. This can be defined as [2, 3].

$$LPSP = \sum_{t=1}^{T} DE(t) / \sum_{t=1}^{T} P_{load}(t)\,\Delta t \quad (18)$$

where $DE(t)$ represents the deficit energy for hour t

In this study the LPSP technique is considered to be the technical implemented criteria for sizing and evaluating a hybrid power generation systems employing a battery bank.

6. ECONOMIC ANALYSIS

The economical model can be presented by the total life cycle costs of the system and the cost of kWh of energy

6.1. Life-cycle cost

The total life cycle costs of the system (*LCC)* represent all the expenditure necessary during the life cycle of the system. It is composed of the initial capital cost of the system. *IC*. and the present value of all maintenance and replacement costs. C_m and C_r respectively over the life of the system.

$$LCC = IC + C_m + C_r \quad (19)$$

The initial capital cost corresponds to the purchase value of the system components and the installation expenses.

$$IC = C_{tot} + C_{ins} \quad (20)$$

where C_{tot} is the total cost of system components and C_{ins} is the installation cost.

<u>Replacement cost</u>

The replacement cost mainly depends on the replacement of some parts of the installation. The present value of replacement cost can be determined as follows [8, 9]:

$$C_r = C_u\, C_n \left[\sum_{i=1}^{N_{rem}} \left(\frac{1+g_1}{1+d} \right)^{(N.i/N_{rem}+1)} \right] \quad (21)$$

where C_n is the nominal capacity/power (battery/inverter). U_c is the unit cost. g_1 is the inflation rate of component replacements and N_{rem} is the number of component replacements over N years.

The total replacement cost is the sum of the individual component replacement costs

<u>Maintenance cost</u>

The estimation of the maintenance cost over the system life cycle is based on the annual maintenance cost which is the sum of individual costs corresponding to the different system components. Generally, the annual maintenance cost can be expressed as a fraction of the component cost.

For the diesel generator, taking into account many assumptions and operating conditions (replacement different filters. oil change and operation). The hourly diesel generator maintenance (Diesel 1500) can be calculated from the following equation [5, 6]:

$$C_{mh,gr}(Euros/h) = \left[\left(0{,}242 + 0{,}3505\, P_{gr}^{n}\right)20 + 74\right]/600 \quad (22)$$

Consequently, the annual diesel maintenance cost can be expressed as follow:

$$C_{ma,dg} = C_{mh,dg}\, h_{dg} \quad (23)$$

where h_{dg} is the overall yearly operating hours.

The present value of maintenance costs (25 years of maintenance) of the hybrid system is expressed as [5, 8, 9]:

$$C_m = \begin{cases} C_{ma}\left(\dfrac{1+g_0}{d-g_0}\right)\left[1-\left(\dfrac{1+g_0}{1+d}\right)^N\right] & d \neq g_0 \\ C_{ma}.N & d = g_0 \end{cases} \quad (24)$$

g_0 is the inflation rate for operations, d is the interest rate. N is the system life in years and C_{m0} is the maintenance cost for the first year.

<u>Operating cost of diesel generator</u>

The cost of a diesel generator operating represents the cost of the consumed fuel amount. The estimation of the diesel operating cost over the system lifetime is based on the annual operating cost which can be given by the following equation:

$$C_{ap,dg} = Q_{hf}\, C_{fuel}\, h_{dg} \quad (25)$$

where C_{fuel} is the fuel price (€/l) and Q_{hf} is the hourly fuel consumption (l/h).

The present value of the diesel operating cost over the system life can be determined from the following equation: [5, 9, 10, 11]:

$$C_{f,dg} = \begin{cases} C_{af,dg}\left(\dfrac{1+g_{fuel}}{d-g_{fuel}}\right)\left[1-\left(\dfrac{1+g_{fuel}}{1+d}\right)^N\right] & d \neq g_{fuel} \\ C_{af,dg}.N & d = g_{fuel} \end{cases} \quad (26)$$

where g_{fuel} is the inflation rate rise in fuel prices

6.2 Levelised cost of energy

The levelized energy cost *LEC* is one of the commonly used indicators for financial performance evaluation of renewable energy based decentralized power supply systems. It represents the cost per unit of energy produced by the system over the analysis period and can be calculated as follows [5]:

(27) $$LEC = \frac{LCC}{E_{tot}} \frac{d(1+d)^N}{(1+d)^N - 1}$$

where E_{tot} represents the annual delivered electricity output of the system

7. RESULTS AND DISCUSSION

The above-presented analysis is applied to given load distribution Fig.3. assumed to be installed at Adrar (southern region of Algeria). The load considered in this study presents the energy requirements of many consumers in remote region in Adrar (southern region of Algeria). The peak demand of the power is 17 kW.

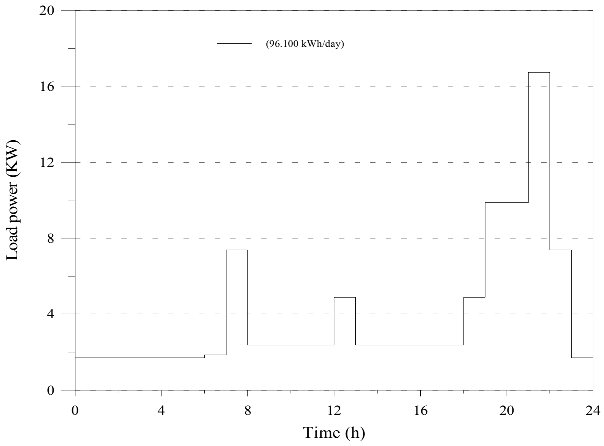

Fig. 3. Hourly load profile.

The simulation was performed by comparing the optimal configurations of stand-alone diesel system, stand alone PV system with battery storage and stand alone hybrid PV/diesel system with battery storage (Fig.1).

The simulation was done with a project lifetime of 25 years. The PV power is varied from 180 W, corresponding to one PV module with a 180 W interval. while the battery storage bank sizes varied from 1 day's energy autonomy to 07 days energy autonomy.

For the system configurations using the diesel generator, diesel generator is generally sized to meet the peak demand of the power. The peak demand of the present case study is 17 kW. In this regard one diesel generator with 18.5 kW (to cover peak load and to cover operation reserve of about 10% to overcome rapid changes in load) has been considered for carrying out the technical and economic analysis of the hybrid systems.

7.1. Stand-alone diesel system

As a starting point, simulation have been performed for Stand-alone diesel system. The simulation results, are presented in Table 1

It can be noticed that for Stand-alone diesel system (18. 5 kW), the operational hours of the diesel generator is 8760 h, the total fuel consumption (l) is about 21100 (l). Based on the diesel price of 0.13 €/l), the levelized cost of energy (LEC) for diesel only system is found to be 0.7533 €/kWh.

7.2 Stand alone PV system with battery storage

The systems simulated consists of different combinations of PV modules supplemented with battery storage bank. The study explores a suitable combination of PV generator and battery storage which can meet the load with zero LPSPS with minimum cost of energy.

The technical and economical parameters of the component system are given [7].

As the first step, the system reliability model is developed in terms of the concept of LPSP. For this purpose, several simulations have been made by considering different combinations taking into account, the power of PV and the capacity storage. The simulation results are presented in Table 1.

As shown in this table, the LEC for the configurations meeting the zero LPSP depends on the storage battery days. Also, there is a minimum LCE point, which corresponds to a specific system configuration (PV power and storage capacity), that guarantees the zero LPSP with minimum LCE.

Taking into account the results presented in Table 1, the configuration system comprising a PV generator (48 kWc) and two days' storage battery is found as the optimal one from both the economical and technical point of view. The levelised cost of energy is obtained equal to 0.7585 €/kWh.

On the other hand, the percentages of the excess electricity produced by the stand alone PV system with battery storage increase with the decreasing of storage capacity defined, in this study, as the autonomy days numbers.

The optimal PV system with battery storage, that guarantees a zero LPSP, products a high energy surplus which can reach 57% of the energy production. Therefore, the use of a third controllable energy source as a back-up electricity source (diesel generator) can reduce the energy surplus while maintaining the LCE at minimum value.

It is observed that with accepting a value of four days' storage battery instead of two days' storage battery, the LEC will get increased by approximately 30% and by 63% for 6 days' storage battery.

Table 1. Technical and economic parameters of PV system with battery storage

Storage battery (days)	PV (kW)	Energy excess part %	PV penetration %	LEC €/kWh
1	93.42	78	100	0,9441
2	48.06	57	100	0,7585
3	41.4	50	100	0,8721
4	34.92	40	100	0,9871
5	28.98	29	100	1,1062
6	24.84	17	100	1,2393
7	23.22	12	100	1,3918

7.3. Stand alone Hybrid PV/diesel system with battery

In this section, the hybrid systems simulated in the present investigation consist of different combinations of PV supplemented with battery bank and diesel generator.

Several simulations have been made by considering different capacities of PV and storage.

The simulation results related to the optimal configurations of hybrid PV/Diesel system for different storage battery are presented in Table 2.

The results show that the optimal configuration for all cases (different battery storage capacity) is obtained for the battery storage of one day of battery storage.

The PV penetration which gives the optimal configuration is about 90% in this case. Then, the optimal configuration PV/Diesel with battery storage for the case considered in this study is composed of PV generator 20.34 kW Diesel generator 18.5 kW one day of storage battery. The LEC is found to be 0.4067 €/kWh (Table 2)

The simulation results show that this hybrid PV/diesel system with battery storage can reduce the excess electricity produced from 57% (PV system with battery) to a 2% (PV/diesel/battery storage) and the levelised cost of energy from 0.7585 to 0.4067 €/kWh.

The effect of PV penetration on diesel operation time and diesel fuel consumption are shown in Fig. 4 and Fig. 5.

The Fig. 4 shows the operational hours of diesel generators as a function of the PV penetration for the optimal configuration of hybrid PV/diesel with battery storage.

Table 2. Technical and economic parameters of hybrid PV/diesel system with battery storage

Storage (days)	PV (kW)	EXC %	Hours of operation (h)	Fuel consump (l)	PV Penet %	LEC €/kWh
1	20.34	7	241	1302	90	0,4067
2	19,08	1	227	1228	90	0.5615
3	19,08	1	201	1084	91	0.7256
4	19.08	1	196	1060	91	0.8904
5	18.72	1	234	1263	90	1.0541
6	18.72	1	234	1292	89	1.2193
7	18.54	1	236	1277	89	1.3829

It is evident from Fig. 4 that as penetration of PV increases, the operational hours of diesel generators decrease. It can be noticed that for diesel-only situation, the operational hours of the diesel generator is 8760.

However, for hybrid PV–diesel system (6.3 kW PV, 18.5 kW diesel system and one day battery storage), which meet the load with zero LPSP with 30% PV penetration, the operational hours of the diesel generator are 1575.

This clearly reflects that operational hours of the diesel generator 18.5 kW of hybrid PV–diesel with one day battery storage (30% PV penetration) system decrease by 82% as compared to diesel-only (0% PV) situation.

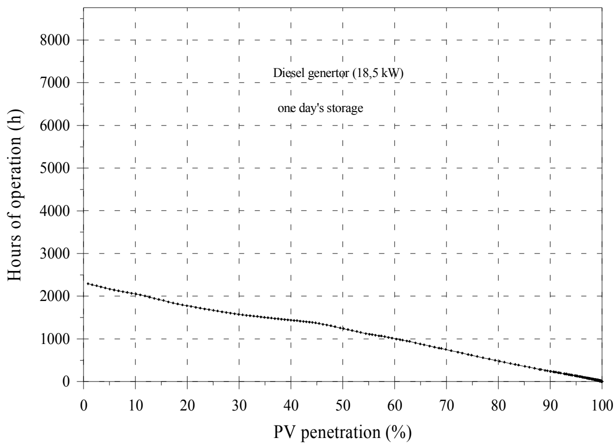

Fig. 4. Impact of PV penetration on diesel generator operation time

8. CONCLUSION

In this paper, the feasibility study of hybridation of diesel power stations with PV energy system is presented.

The studied energy systems include stand-alone diesel system, stand alone PV system with battery storage and PV/diesel system with battery storage.

The diesel only system can cause many environment problems in a long term view. In this study, the cost of energy produced by the diesel system is 0.7533 €/kWh.

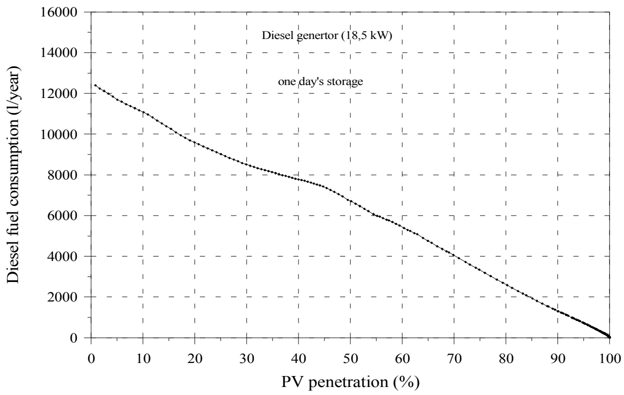

Fig. 5. Impact of PV penetration on diesel fuel consumption

The optimal hybrid PV/system with battery storage that guarantees a zero LPSP, products a high energy surplus which can reach 57% of the energy production. Therefore, the use of a diesel generator can reduce the energy surplus while maintaining the LEC at minimum value.

The simulation results show that the optimal configuration of a hybrid PV/diesel system with battery storage, which gives the minimum LEC, is composed of 20.34 kWp PV generator together with 18.5 kW and a battery storage of one day of autonomy. The LEC is found to be 0.4067 €/kWh and the PV penetration is 90%

The hybrid PV-battery-diesel configuration offers several advantages such as diesel efficiency can be maximized; diesel maintenance can be minimized and a reduction in the capacities of diesel and battery can occur.

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