ANALYSIS OF THE SELF-CONSUMPTION POSSIBILITIES IN SMALL GRID-CONNECTED PHOTOVOLTAIC SYSTEMS IN SPAIN

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ABSTRACT: This paper analyzes the self-consumption possibilities of the local electricity generated in a grid-connected to low voltage PV system. In particular, it focuses on theoretical and simulated studies of the energy flows and exchanges that take place within the system and the influence that Demand-Side Management and storage systems have. Different factors based on the energy flows of the system have been defined for the study. Finally, an economic study, focused on the profitability shown by the self-consumption, has been included.
Keywords: Demand-Side Management, Storage System, PV Distributed Generation, Self-consumption, Electrical Rate-setting.

1 INTRODUCTION

Different studies, found in the literature, have concluded that Demand-Side Management (DSM) is beneficial to the grid, both retailers and users [1-3]. In addition, by combining DSM with PV Distributed Generation systems these benefits are increased by taking into account the local generation in the DSM algorithms. In this situation, the concept of self-consumption arises. The self-consumption represents the electrical energy consumed by the loads, which is supplied by the local generation sources [2].

Self-consumption is emerging as a new possible operating mode for PV grid-connected systems. Self-consumption avoids losses in the transport of electricity because it is generated in the same place where it is consumed. In addition, users can reduce the electricity bill using its own generated electricity, and in some countries, they even gain a financial incentive by self-consuming electricity rather than selling it to the retailers (existing in Germany since 2009 [4] and currently under discussion in Spain [5]). This fact, together with the rising prices of the retail electricity and the less attractive feed-in-tariffs for PV, suggests that new operation modes for PV Distributed Generation systems should be explored, different from the traditional approach based on maximizing the exported electricity to the grid. However, not only economic benefits are expected; a higher efficiency in the electricity use is also expected as well a greater user participation in electricity markets [1]. Additionally, self-consumption and new regulatory frameworks with time-dependent electricity tariffs are two factors to consider in the implementation of load management solutions and specifically in the design of PV Distributed Generation systems.

This paper aims to analyze the feasibility of the self-consumption of the electricity produced by PV systems integrated in residential and small commercial grid-connected buildings and with an electrical storage system.

2 ELECTRICAL STUDY

An electrical analysis has been made to a better understanding of how the self-consumption of local generated electricity works. The electrical study has been carried out on an electrical system inspired on the energy self-sufficient house prototype “MagicBox” [2,3].

2.1 System under study

The electrical system has been implemented based on an AC bus topology. It consists of a PV generator connected to the grid, with electricity storage through batteries and a set of loads. Figure 1 shows a block diagram where all the electrical elements can be observed. The arrows shown next to the power variables (related to the PV system, batteries, grid and loads: P_{pv}, P_{bat}, P_{grid} and P_{load} respectively) indicate the positive sign criteria adopted in our study.

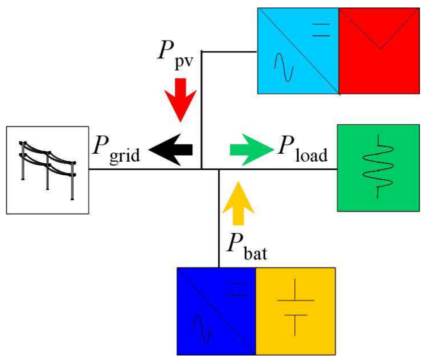


Figure 1: Block diagram of PV hybrid system installed in a typical grid-connected building.

To establish a design condition based on the self-consumption term, it is necessary to cover different PV generators sizes. So that, in the simulations carried out the PV generator nominal power is variable. The inverter used in the simulations consists of a Transformer-Less (TL) inverter, which has a high efficiency and its nominal power is related with the PV generator with a factor of 0.9.

The storage system is composed of a lead-acid battery with 6 kWh of capacity and a battery inverter of 5 kW of nominal power. It is managed with the objective of maximizing the self-consumption [3]. In order to optimize the local consumption of PV electricity, either immediately or deferred over time through local storage, the battery operation is set independent of the grid. This means that batteries are not allowed to be charged from the grid, nor be discharged to it.

To model the load consumption of the electrical system, we have used three different demand profiles. The first profile has the form of the aggregate demand of the residential sector, but its consumption is the average consumption of a domestic user ($P_{load,1}$ in Figure 2) [6]. In the second one we have followed the same method, but for the commercial sector ($P_{load,2}$ in Figure 2) [6]. Finally, the third profile is based on a single domestic user consumption profile, which is composed of the typical appliances of a highly electrified home ($P_{load,3}$ in Figure 2) [2,3].

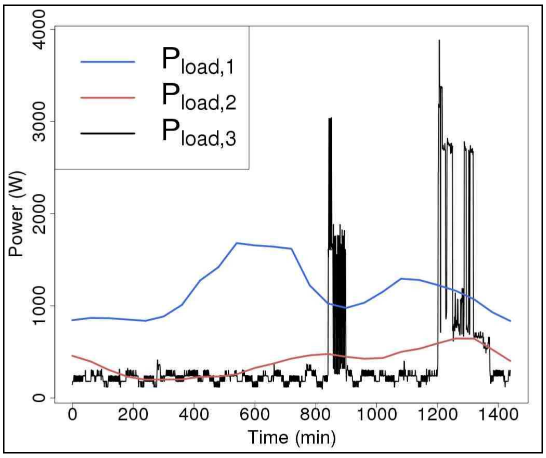


Figure 2: Load profiles.

2.2 Self-consumption factors

To analyze the possibilities of self-consumption of the local generation, we have defined two factors. The first one is the Self-consumption factor (ξ), defined as the electricity consumed locally from local sources of generation. It also includes the electricity provided by the storage systems (remember that only PV electricity is stored).

The Self-consumption factor has two variants depending on the term used to normalize the factor. One is defined as the fraction of load that is supplied (directly and indirectly) from the PV system (ξ_L, see Equation 1.a) and the other one is the fraction of generated electricity that is used to supply the loads (ξ_G, see Equation 1.b).

$$\xi_L = \frac{E_{\mathrm{pv,load}} + E_{\mathrm{bat,load}}}{E_{\mathrm{load}}} \tag{1.a}$$

$$\xi_G = \frac{E_{\mathrm{pv,load}} + E_{\mathrm{bat,load}}}{E_{\mathrm{G}}} \tag{1.b}$$

where $E_{\mathrm{pv,load}}$ is the PV electricity feeding the loads, $E_{\mathrm{bat,load}}$ is the electricity extracted from the battery to the loads, E_{load} is the electricity consumed by the loads and E_{G} is the local generated electricity ($E_{\mathrm{G}} = E_{\mathrm{pv}} + E_{\mathrm{bat,load}}$).

ξ_L expresses the independence that the user has over the grid while ξ_G represents the efficiency of the local generated electricity to meet the demand of a user. Since the direct and indirect local use of PV production ultimately depends on the demand, it can be concluded that $\xi_L \in [0,1]$ and $\xi_G \in [0,1]$, however, the meaning of each factor is different. $\xi_L=0$ would be the case of a building with no local generation available, and $\xi_L=1$ the case of a building with an autonomous —physically or functionally— PV system. While, $\xi_G=0$ means that all the generated electricity goes to the grid and the user does not self-consume anything, $\xi_G=1$ means that all the generated electricity supplies the local demand. It should be noted that both proposed factors could be used in different time frames. In addition, because they are normalized, comparisons between the Self-consumption factors of PV systems with different sizes and loads are possible.

3 ECONOMIC STUDY

To analyze the economic viability of the system under study, we have used the Net Present Value (NPV) per W_p cost using the model described in [7]. The NPV represents the present value of an investment through benefits and costs related with the operation of the PV system. It is calculated as follows:

$$NPV_{Wp} = [Benefits - Costs]_{Wp} \tag{3}$$

where, $[Benefits]_{Wp}$ are expressed in Equation (4) and $[Costs]_{Wp}$ are described by Equation (5).

$$[Benefits]_{Wp} = \frac{1}{C_{Wp} \cdot P_{nom}} \cdot \frac{p_{ef} \cdot E_{sc} + p_{tg} \cdot E_{tg}}{(A/P, r'_e, N)} \tag{4}$$

where, C_{Wp} is the initial system cost or capital cost (per installed W_p), P_{nom} is the nominal power of the PV generator (W_p), p_{ef} is the price of the electricity imported from the grid (€/kWh), E_{sc} is the electricity consumed from local sources of generation, p_{tg} is the price of the electricity exported to the grid or Feed-In Tariff (FIT), E_{tg} is the electricity exported to the grid, $(A/P, r'_e, N)$ is the capital recovery factor for the rate r'_e in N years of system lifetime and the rate $r'_e = \frac{r - r_e}{1 + r_e}$, where r is the discount rate and r_e is the market energy escalation rate.

$$[Costs]_{Wp} = \left[F_{financ} + \frac{f_{OMI}}{(A/P, r'_e, N)} \right] \tag{5}$$

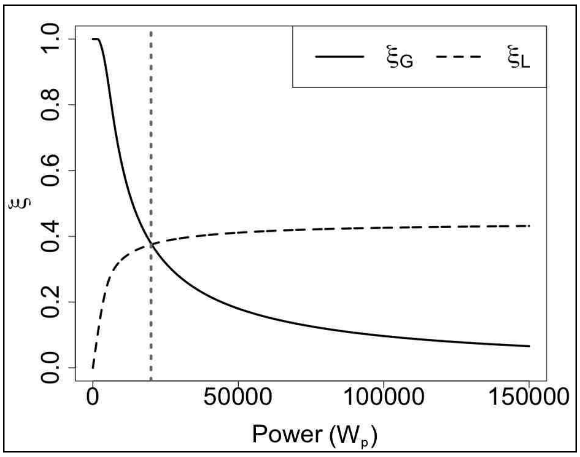
$$F_{financ} = f_p + (1 - f_p - \tau_{subv}) \cdot \frac{(A/P, r_1, N_1)}{(A/P, r, N)} - \tau_{inc} \cdot f_{dep} \tag{6}$$

where, F_{financ} included different financial possibilities (downpayment, subventions, loans and taxes related with depreciation), f_p is the downpayment factor (fraction of capital cost), τ_{subv} is the tax subvention, r_1 is the market loan interest rate, N_1 is the loan period, τ_{inc} is the incremental income tax rate, $f_{dep} = \frac{1}{N_d \cdot (A/P, r, N_d)}$ is the straight-line depreciation of the PV installation over N_d years and f_{OMI} is the annual operation, maintenance and insurance cost.

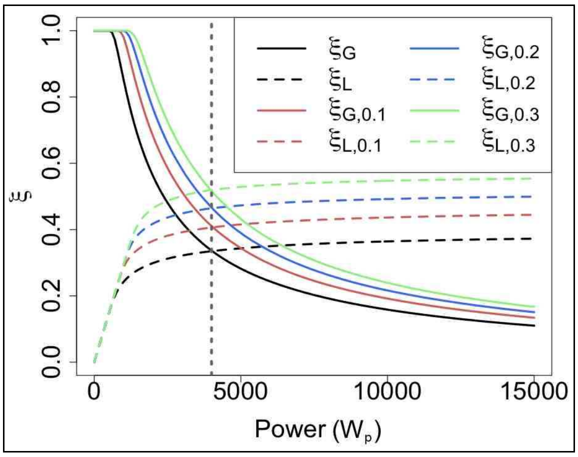
Finally, the capital recovery factor for a rate r in N years is given by:

$$(A/P, r, N) = \begin{cases} \dfrac{r}{1 - (1+r)^{-N}} & if \quad r \neq 0 \\ \dfrac{1}{N} & if \quad r = 0 \end{cases} \tag{7}$$

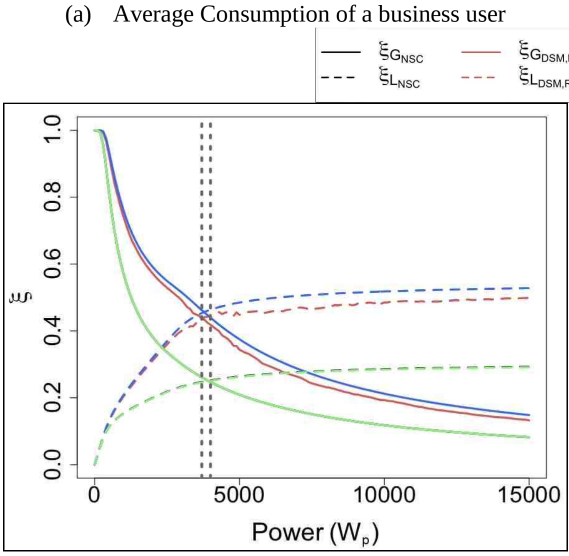
This method for calculating the NPV is convenient to handle not very large figures and to establish when investing in a PV system is economically profitable: if the NPV value is positive, the installation is profitable.



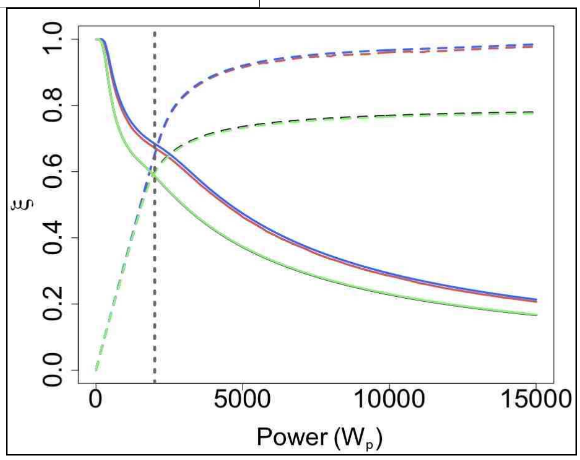
(a) Average Consumption of a business user



(b) Average consumption of a domestic user



(c) Single domestic user without battery



(d) Single domestic user with battery

Figure 3: Self-consumption factor of the three different consumption load profiles.

4 RESULTS

The results are obtained trough yearly simulations of a PV system made of crystalline PV modules, located in Madrid with south orientation and optimum inclination (β=35º). Simulations have been performed using a Typical Meteorological Year (TMY) [8]. In the simulations, the elements of the system under study have been configured in different ways. We have simulated the system with and without the battery to see the effects of a storage system in the self-consumption. In addition, the simulations have been made with the three different load profiles to see the differences between domestic and business users and between average consumption profiles and a real consumption of only one user.

Furthermore, we have used different strategies of Demand-Side Management. DSM is defined as actions that influence the way consumers use electricity in order to achieve savings and higher efficiency in energy use [9] and its combination with an automatic control of the household demand leads to a new concept called Active Demand-Side Management (ADSM) [1-3]. In this paper, we have implemented a load shifting strategy for the ADSM. However, we used two different objectives to implement it: (i) displacement to the "valley hours" of the demand curve (minimum demand in aggregate terms, VDSM) and (ii) displacement to the maximum of the generated electricity (self-consumption maximization). To implement the load shifting with the objective of maximizing the self-consumption, a forecast of the PV generation for the next day is needed [10]; for the displacement of the demand to the valley a forecast curve of the average consumption of the day is necessary. We have used two different PV forecasted generation profiles: one corresponding to simplified estimations used in Spanish legislation (Royal Decree 661,[11]) (DSM,RD), and an optimum forecasted profile (DSM,O) which is equal to the actual PV generation profile of the next day. However, we can only displace an amount of the electricity demand along the day or "deferrable" load. In the case of a domestic user the "deferrable" load is typically a 20% of the total (corresponding to the washing-machine, the dryer and the dishwasher) [3]. However, for a business user there is typically no "deferrable" load because consumption mainly occurs at times of PV generation.

4.1 Electrical results

The results of the yearly simulations of the Self-consumption factors can be observed in Figure 3. For all the cases, Figure 3 shows that the bigger the size of PV system is, the higher ξ_L is. In contrast, ξ_G decreases its value when the size of the PV generator grows, being oversized with respect to the demand. In general, the ξ_L reached without using ADSM techniques or storage system is less than half of the demanded energy by the user. However, using ADSM techniques and/or storage system increase the self-consumption factor.

Figure 3(a) shows the results of the average consumption of a business user without storage system and the maximum ξ_L reached is about 0.4. However, ADSM could not be applied because there is no "deferrable" load. In the case of the average consumption of a domestic user, the maximum ξ_L reached without using ADSM is around 0.35 (see Figure 3(b)). However, applying ADSM techniques increases the value of ξ_L and the level reached depend on the amount of "deferrable" load (the bigger the amount of "deferrable" load, the higher the level reached is). For this user, we have simulated the effect of three amounts of "deferrable" load, 10%, 20% and 30% (in red, blue and green respectively in Figure 3(b)), for which the maximums ξ_L are about 0.45, 0.5 and 0.55 respectively.

With these two average users, we have studied the self-consumption in general, but it is necessary to study the self-consumption with a single real user. Figure 3(c) shows the results of a single domestic user without a storage system; in this case the maximum ξ_L reached for natural self-consumption (without using ADSM, NSC in black colour, which is below the green one in Figures), is about 0.3. This result matches up with the one corresponding to VDSM (in green). However, the results obtained applying ADSM to maximize the self-consumption (DSM,RD in red and DSM,O in blue) are higher than the ones reached before, 0.5 for DSM,RD and 0.53 for DSM,O. The difference between these two results is the error of the forecasted PV generation profile. If we introduce a storage system, all the previously results increase their values (see Figure 3(d)). For all the cases, ξ_L is doubled and reduces the error between the forecasted generation profiles. With a storage system and an ADSM system is possible to supply all the user demand with local generated electricity.

In addition, there is an intersection point between ξ_L and ξ_G for all the cases in Figure 3. This point ($\xi_L = \xi_G$) represents that the annual electricity generated locally is equal to the annual electricity consumed by the loads (see Equations 1.a and 1.b). For all the cases without the storage system, the value of $\xi_L = \xi_G$ departs from the maximum less than 10% and by using a storage system this point departs from the maximum less than 30%. The corresponding PV generator sizes are gathered in Table I. The PV generator size for the domestic user profiles without using a storage system is five times lower than the average business user, which is about the same relationship of the daily consumed electricity between these users. The use of a storage system reduces the PV size of the intersection to half the size without using it.

Table I: PV generator sizes in kW_p for $\xi_L = \xi_G$.

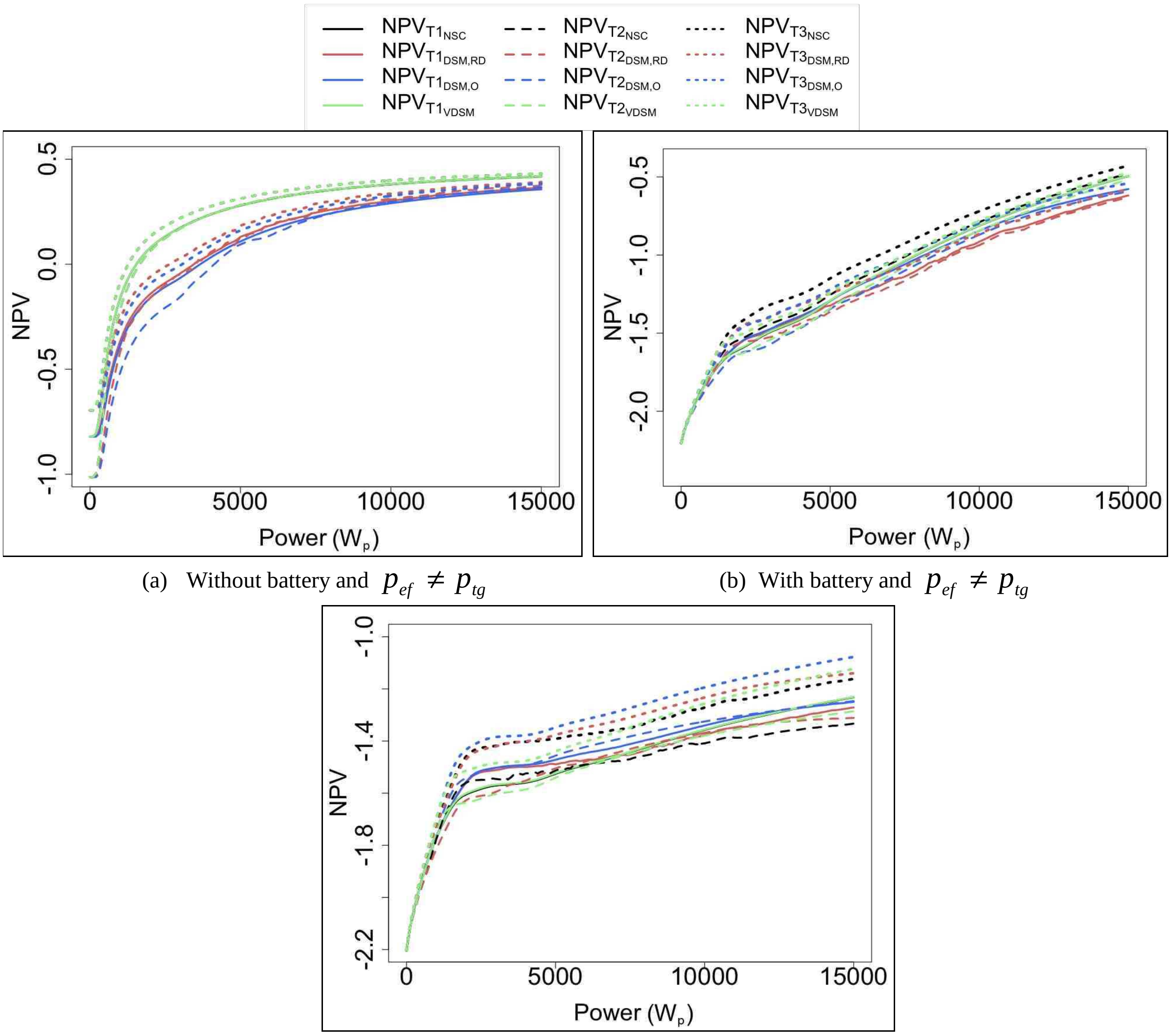
Figure 3	**$P_{nom}(\xi_L=\xi_G)$ [kW_p]**
(a)	20
(b)	4
(c)	≈ 4
(d)	2

4.2 Economic results

The simulations analyze the NPV per W_p cost of an electrical system like the one described in Section 2.1. The NPV evaluates the electrical system in a 25 years period. These simulations have taken into account the different configurations of the electrical system (with or without the storage system) and techniques used to the enhancement of the self-consumption. The user profile selected to this study is the load profile corresponding to a single domestic user.

The initial investment cost of the PV system without batteries has been set at 3€/W_p and the initial investment cost of the storage system has been set to 0.97€/W for the battery inverter and 13.57€/Ah for the battery. The electrical information is constant yearly and is obtained from the study made before. Three tariffs have been defined to study their effect in the profitability of the system: i) **T1**, single tariff with no discrimination period of time, which is called "Last Resource Tariff" (LRT) and its value is 14c€/kWh, ii) **T2**, tariff with two periods of time discrimination, which values are 16c€/kWh for peak-on periods (winter: 12-22 h., summer: 13-23 h.) and 6c€/kWh for peak-off periods (winter: 22-12 h., summer: 23-13 h.) and iii) **T3,** hourly discrimination tariff, which consists of a different prices of electricity for each hour of the day depending on the average consumption of a domestic user; the average price of this tariff is 14c€/kWh as the price of T1. The Feed-In Tariff (FIT) considered has a value of 28c€/kWh, applicable to PV systems under 20 kW in Spain in 2011 [12]. Half of the funds are owned resources and the other half of the funds is a loan with an interest rate of 5% repayable over 10 years. The depreciation period is 15 years and the operating and maintenance costs are the 1% of the investment cost of the PV system. Finally, the discount rate is set to 3% and the annual incremental rate of the electricity price is set to 2%.

The results of NPV per W_p cost obtained are summarized in Figure 4. Figure 4(a) shows the profitability of the system under study without the storage system. In this case the results of the NSC and VDSM are the same because the consumption of electricity is the same. The profitability in this scene is reached from 2kW_p onwards, and the maximum profitability reached at the end of the investment lifetime is 0.4. However, with ADSM techniques to maximize the self-consumption the profitability is reached from 4kW_p onwards, which is the double size of the previous case, and the maximum profitability reached at the end is 0.35. This increase can be explained by the lower revenues from exported electricity derived from implementing ADSM under the considered scenario (current Spanish regulations). It can be also observed that among the three tariffs selected the most profitable would be T3. However, with the incorporation of a storage system, there is not any profitable PV size generator (see Figure 4(b)). The reason is that the initial investment of the system is higher due to the cost of the storage system. Thus, it is necessary to reduce the storage system costs. In addition, the profitable differences between NSC and ADSM of self-consumption maximization have been reduced. Again the most profitable tariff is T3 and the maximum profitability reached at the end of the investment lifetime is -0.5.



(a) Without battery and $p_{ef} \neq p_{tg}$

(b) With battery and $p_{ef} \neq p_{tg}$

(c) With battery and $p_{ef} = p_{tg}$

Figure 4: Net Present Value of a single domestic user.

Finally, Figure 4(c) represents the profitability of a scenario in which the price of the FIT is equal to the price of the purchased electricity. It can be observed that there is not profitable PV size generator because now the revenues are lower than in the other two cases and the system has a storage system. In this case the ADSM techniques to maximize the self-consumption get better profitability than NSC and VDSM. The most profitable tariff is again the T3 for DSM,O with a value of -1.2 at the end of the simulation.

In view of the results it is stated that a reduction in the costs of the PV systems and the storage systems is necessary. Another measurement that would stimulate the self-consumption of PV electricity is the recognition of the added value of PV technology (market and non-market values) in terms of tariff incentives [13]. In this way the PV sector will be prepared to the arrival of the grid parity.

5 FINAL REMARKS AND CONCLUSIONS

In this paper the self-consumption of the local generated electricity has been analyzed from an electrical and an economic point of view. The system under study consists of a PV generator connected to the grid with a storage system and different load consumption.

The self-consumption factors (ξ_L and ξ_G) are not directly proportional to the size of the PV generator and are important design criteria for PV grid-connected systems in the framework of Smart grids with high penetration of Distributed Generation. The tendency of ξ_L is to increase with the PV generator size, while ξ_G decreases its value. Demand-Side Management techniques improve the rate of the self-consumed electricity, and together with storage systems reduce drastically the electricity consumed from the grid. In addition, DSM and/or storage systems relatively small sizes of PV generators are sufficient to achieve high self-consumption levels (>60% of annual PV generation or load consumption).

An interesting PV generator size is when $\xi_L = \xi_G$ because it means that the consumed electricity is equal to the generated electricity. In this point the maximum of ξ_L is almost reached (difference < 10% of maximum).

Increasing the self-consumption makes the exchanges with the grid smaller. The imported electricity from the grid could be reduced to zero in the case of using a storage system combined with an ADSM system managed to maximize self-consumption. The reduction of exchanges with the grid lead to savings, however it also involves economic losses, under prevailing Spanish regulations, due to less surplus of electricity.

Under existing PV and Low Voltage electricity tariffs conditions in Spain, there is a profitable size of PV systems when there is no electrical storage (stationary batteries considered). However, there is still no profitability when the system includes storage. This highlights the needs to reduce PV system costs and promote self-consumption (for example, via tariff incentives) in the transition towards Distributed Generation powered Smart Distribution Networks.

6 ACKNOWLEDMENTS

M. Castillo-Cagigal is sponsored by the Spanish Ministry of Education with a Ph.D grant (FPU-2010). The authors want to thank the companies SMA, for the PV system components and Siemens, for the automated appliances and the Escuela Técnica Superior de Ingenieros de Telecomunicación of the UPM for their support in the construction and maintenance of “Magic Box”.

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