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SELF-CONSUMPTION ENHANCEMENT WITH STORAGE SYSTEM AND DEMAND-SIDE MANAGEMENT: GEDELOS-PV SYSTEM

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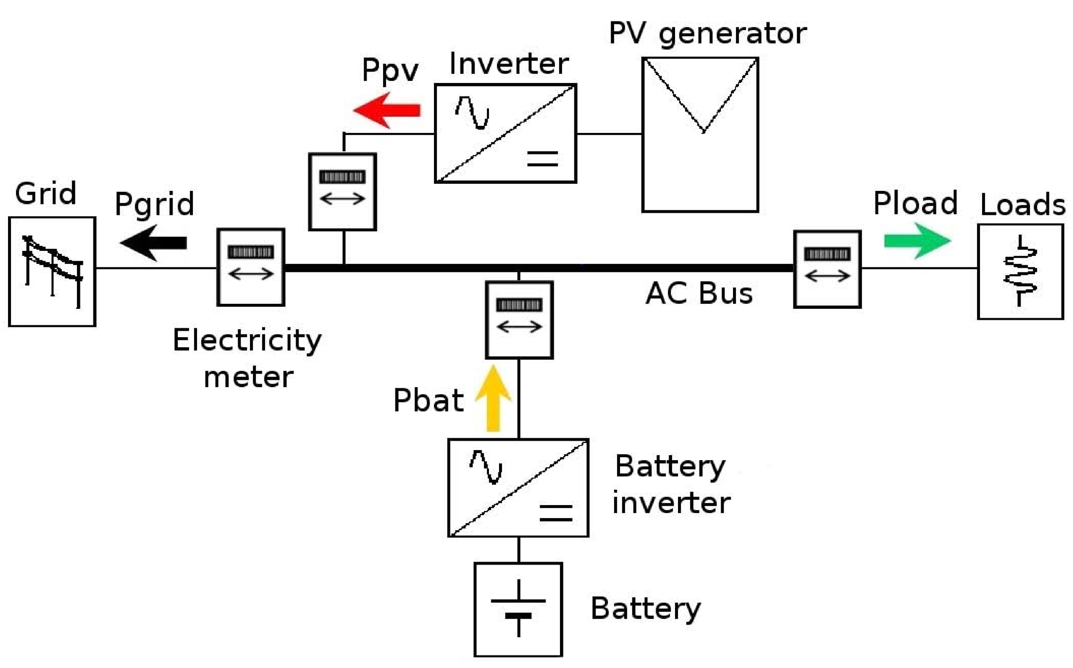
GeDELOS-PV system



The GeDELOS-PV system is an example of added value for PV electricity arising from the combination of modern hybrid PV technology with a lead-acid battery storage system and Demand Side Management (DSM) strategies in the residential sector. The main objective of this system is to satisfy the user demand by optimizing the use of PV electricity. In order to achieve this objective we have followed two strategies:

- The management of an small scale battery storage system in order to use PV electricity indirectly
- To schedule the local electricity demand in order to integrate the user demand and local PV generation patterns

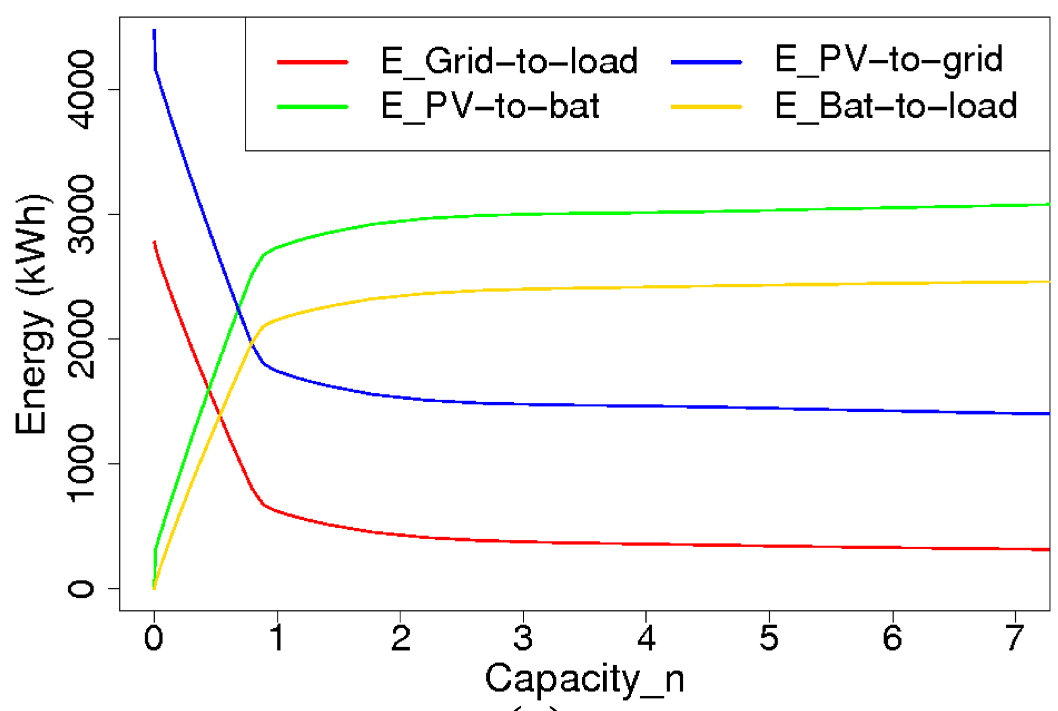
We have developped a software battery controller with the objective of maximizing the self-consumption. The principal characteristics of this controller are:

- To manage the battery inverter's current. This inverter has current limiters, with them we can modify the power flows.
- The battery controller does not allow the electricity exchange with the grid. The inverter and the grid are physically connected. By controlling the currents the controller only charges the battery with PV energy and only discharges the battery to supply the house demand.
- Preserve the battery against overcharge and overdishcharge.

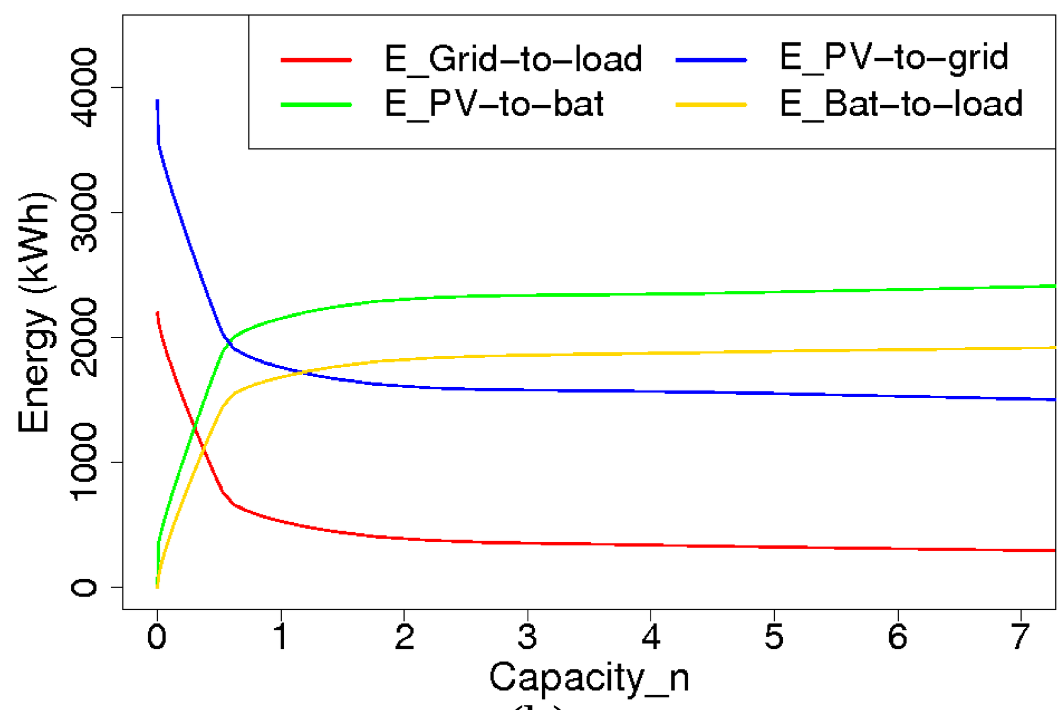
In order to evaluate the operation results we have defined a self-consumption factor (ξ), where $E_{PV\,to\,load}$ is the PV energy to the loads, $E_{Bat\,to\,load}$ the energy from the battery to the loads and E_{Load} the total energy consumed:

$$\xi = \frac{E_{PV\,to\,load} + E_{Bat\,to\,load}}{E_{Load}}$$

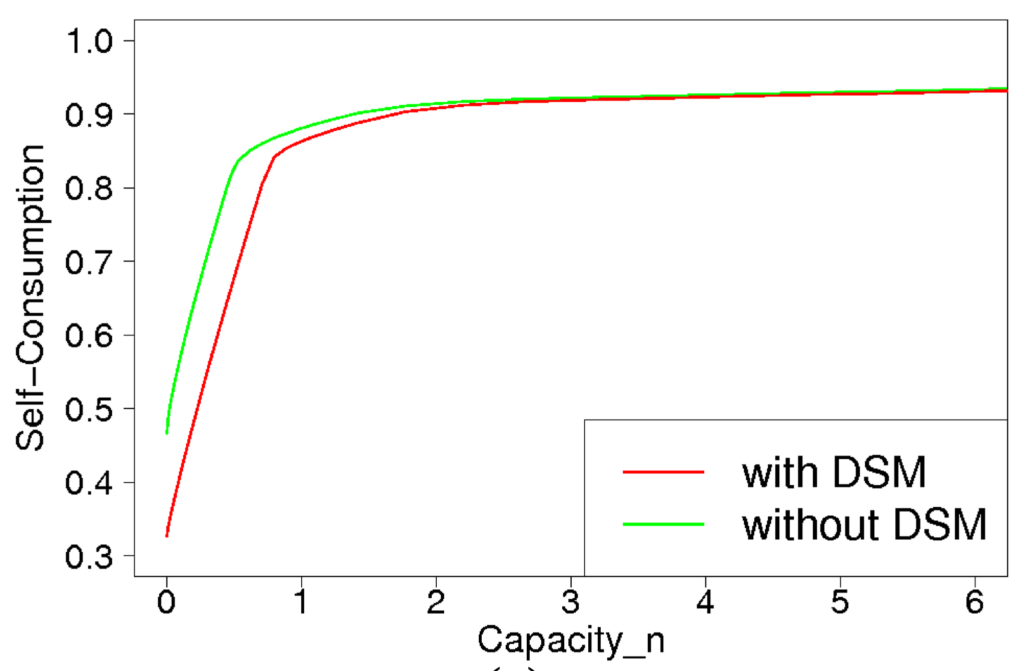
Simulated results (Yearly)



(a)



(b)

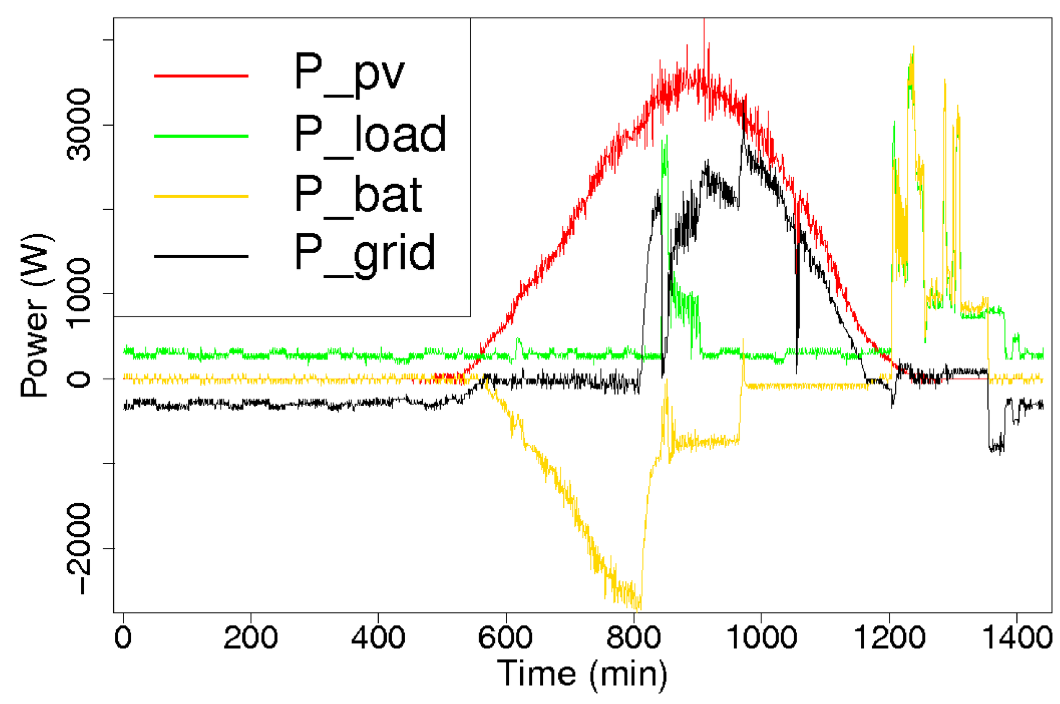


(c)

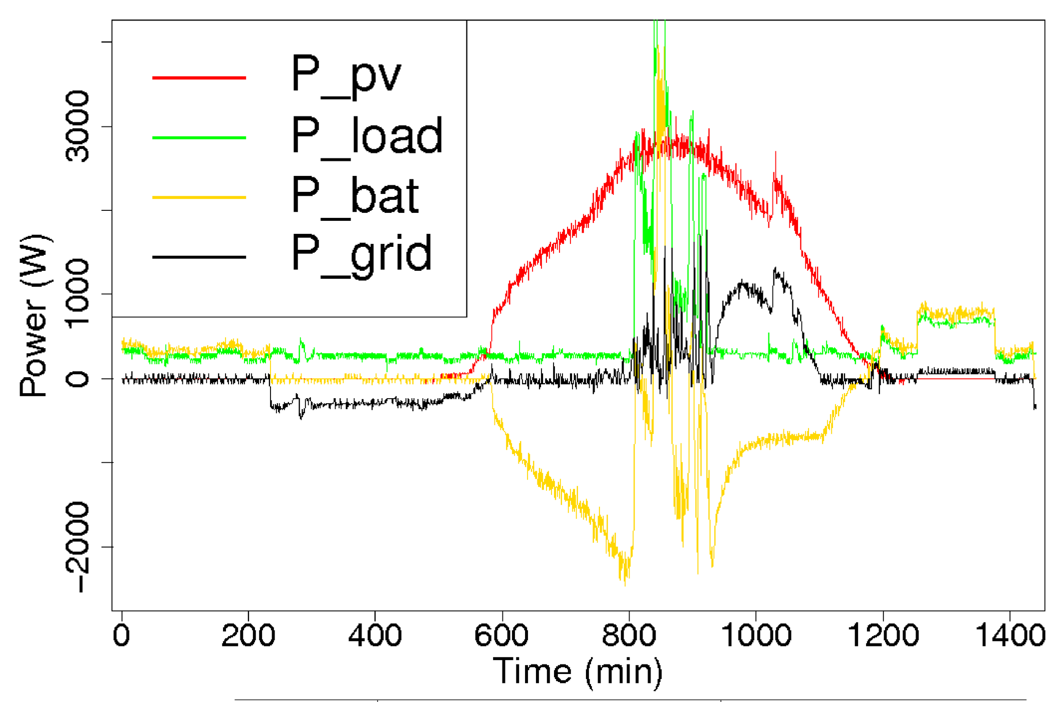
Cap_n^*	ξ without DSM	ξ with DSM
0	0.328	0.468
0.2	0.468	0.626
0.5	0.638	0.794
0.8	0.806	0.858
1	0.85	0.871
3	0.910	0.915
∞	1.0	1.0

[*] Capacity is normalized by the daily consumption in order to represent it in days of autonomy.

Experimental results



(a)



(b)

Cap_n	ξ Fig. a without DSM	ξ Fig b ξ with DSM
0.5	0.693	0.847

Conclusions

The self-consumption factor is not directly proportional to the capacity level and it is an important design criterion for an energy system. The DSM improves the energy behavior controlling only a part of the electricity demand, and its effects are similar to a small storage system.

The combination of both techniques can perform the energy behavior more efficiently and increase the use of PV electricity. These two strategies will play an important role in the smart grids. By combining multiple systems like this one, we can implement a more complex energy behavior and improve the use of the PV electricity.

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ABSTRACT: Because of the recent technological developments within the field of power conditioning and the progressive decrease of incentives for PV electricity in grid-connected markets, new operation modes for PV systems should be explored beyond the traditional maximization of PV electricity feed-in. We have developed the GeDELOS-PV system as an example of added value for PV electricity which arises from the combination of modern hybrid PV technology with a lead-acid battery storage system and Demand Side Management strategies in the residential sector. We carry out simulations for long-time experiments (yearly studies) and real measurements for short and mid-time experiments (daily and weekly studies). Results show that the relationship between electricity flows and storage capacity is not linear and therefore, it becomes an important design criterion.
Keywords: Demand-Side, lead-acid battery and battery controller and photovoltaic.

1 INTRODUCTION

The growing penetration of Distributed Generation (DG) technologies in grid-connected applications has increased the need for efficient integration technologies. The penetration of PV generation is increasing worldwide, achieving for example 9.8 GW in Germany and 3.5 GW in Spain of the total installed power at the end of 2009 [1]. However, the renewable energy operation and the grid stiffness limit the amount of the installed power. Therefore, it is hard to increase of this sort of energy in places where its presence is currently high. The work presented in [2] concludes that the use of load shifting and energy storage is compulsory to achieve high PV penetration levels.

Demand-Side Management (DSM) is defined in this paper as actions that influence the way that consumers use electricity in order to achieve savings and higher efficiency [3]. Furthermore, DSM has been identified as one of the main strategies to be promoted in order to guarantee security of supply in the European Union [4]. The combination of DMS with new-generation PV hybrid technology (grid connected-type inverters with small-scale electricity storage and an active control of the grid interface) leads to a new concept called “Active Demand Side Management” (ADSM). From which not only PV systems operators can profit, but also other consumers connected to the same grid (through cooperative strategies) and the grid itself (if the PV systems respond to signals coming from the Distribution System Operator).

2 GeDELOS-PV SYSTEM

The GeDELOS-PV system is an example of added value for PV electricity which arises from the combination of modern hybrid PV technology with a lead-acid battery storage system and DSM strategies in the residential sector. It has been developed on a prototype of a self-sufficient solar house called “MagicBox” [5], consisting of a 7 kWp PV generator, 7.7kWp grid-connected inverters, 36 kWh of lead-acid battery storage capacity with a 5kWp battery inverter and electricity meters. It includes electrical appliances typical of a highly electrified home. The most consuming ones (kitchen and laundry appliances) can be remotely controlled using Information and Communications Technologies.

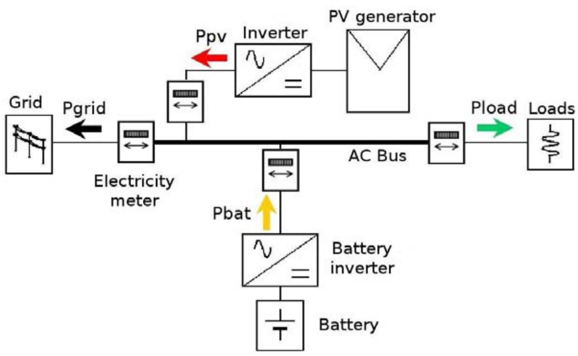


Figure 1: Esletrical system sketch

Figure 2: Frontal view of MagicBox

The main objective of the GeDELOS-PV system is to satisfy the user demand, optimizing the use of PV electricity. To achieve this objective we have followed two main strategies: i) The management of an small scale battery storage system in order to use the PV electricity indirectly and ii) to schedule the local electricity demand in order to integrate the user demand into local PV generation. Different constraints can be implemented using these strategies: limitation of energy demanded from the grid, restriction of hours at which energy can be exported or imported, etc. The GeDELOS-PV system operation is focused on the self-consumption maximization. It maximizes the amount of electric energy consumed by loads which is supplied by the local generation sources (PV generation in our case). We have defined a self-consumption factor (ξ) as:

$$\xi = \frac{E_{\text{pv,load}} + E_{\text{bat,load}}}{E_{\text{load}}} \quad (1)$$

where $E_{pv,load}$ is the PV energy directly consumed by the loads, $E_{bat\,,load}$ is the demanded energy supplied by the battery and E_{Load} is the total amount of demanded energy.

Notice that the proposed factor can be used in different time-frames. Moreover, because ξ is normalised by the loads demand $\xi \in [0,1]$, it allows to comapre systems with different sizes and loads. ξ=0 would be the case of a building with no local generation available, and ξ=1 when all the energy is locally supplied.

3 BATTERY CONTROLLER

As aforementioned, the house is equipped with a lead-acid battery bank. The battery bank is divided in 24 cells; each cell has a capacity of 750Ah and a voltage of 2V. Therefore, the total battery bank voltage is 48V with a capacity of around 36kWh. Because this capacity value is high for a single house, whose daily consumption is around 11kWh, we do not use the total capacity in our experiments.

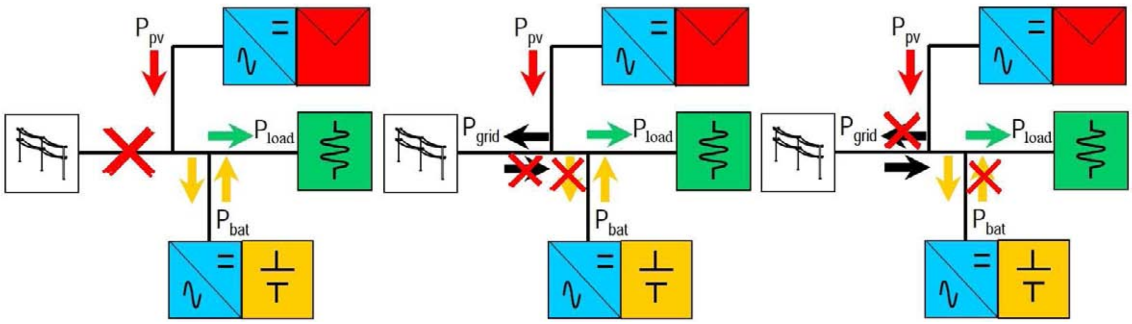


Figure 3: Battery controller operation sketch: a) Self-Consumption, b) overcharge and c) overdischarge.

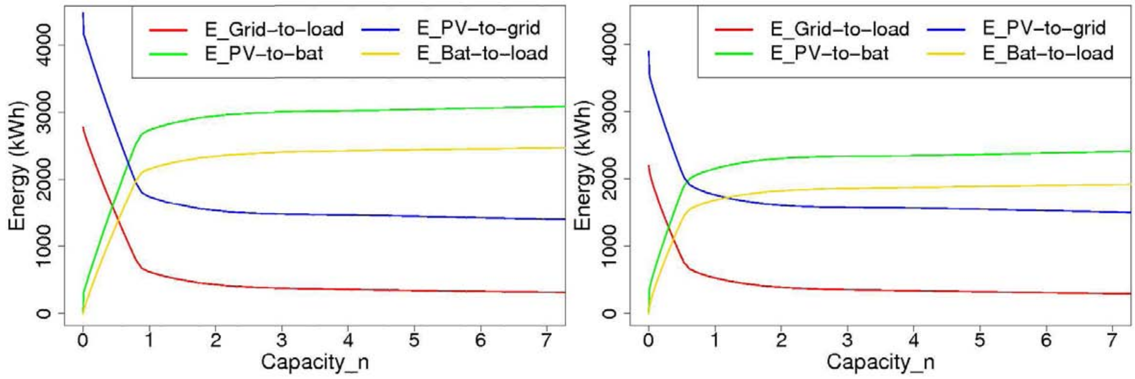
In order to use the stored electricity, the house is equipped with a battery inverter. This inverter does not only carry out the energy conversion, but allows to control the power flows in the house. By making use of these stream controllers, several high-level (software) battery controllers have been developed and tested. The objective of theses controllers is to maximize ξ, and their main characteristics are: i) management of the battery inverter's currents, ii) avoidance of electricity exchange with the grid (they only charge the battery with PV generation excess and discharge the battery to supply the loads) and iii) preservation of the battery against overcharge and overdischarge. The one that performs best in terms of maximizing ξ, defines the following states depending on the battery State of Charge (SoC):

- Self-Consumption (Figure 3.a): 25<SoC(%)<95. Grid-connection is physically maintained, but interchanges of electricity with the grid are minimised.
- Overcharge (Figure 3.b): SoC(%)≥95. The battery supplies the loads and the battery controller regulates the charging process by means of a specific function that dynamically controls the input power. This strategy smoothes the power input curve as well as the system response until the battery enters into the "Floating mode" (SoC=100%), where it is controlled exclusively by the battery inverter.
- Overdischarge (Figure 3.c): SoC(%)<20. The battery ceases supplying the loads, battery charging is only allowed if the PV generation exceeds the loads demand.

4 SIMULATION RESULTS

Simulations have been performed using one-year of real PV generation data as an input to GeDELOS-PV system. To represent the user demand, a constant daily consumption of 11.3kWh has been considered. 21.5% of the daily consumption is controllable (washing machine, dryer and dishwasher). The simulations have been made for different storage capacities and with and without DSM. The battery capacity is normalized by the daily consumption in order to represent capacity in days of autonomy:

$$C_{\text{n}} = \frac{C_{\text{bat}}\ (\text{kWh})}{E_{\text{load}}\ (\text{kWh})} \quad (2)$$



(a) (b)

Figure 4: Relation between electricity flows and normalized capacity for yearly studies: a)withput DSM and b) with DSM.

The main electricity flows analyzed are $E_{Grid,load}$, $E_{PV,grid}$, $E_{PV,bat}$ and $E_{Bat,load}$. In Figures 4 the relation of these variables with the normalized capacity can be observe without (a) and with DSM (b) respectively. Notice that for low capacity levels, the electricity flows variate severely. When capacity is close to one day of autonomy ($C_n \approx 1$), this tendency changes and begins to be softer. For high capacity levels, the functions saturate and achieve a plateau value. Figure 5 summarises the annual simulation results. It shows the evolution of the Self-Consumption factor with and without DSM strategies, for different storage capacities. Table 1 includes some representative ξ values for the yearly study using daily averages. Notice that for $C_n = 0$ the use of DSM performs a $\xi = 0.468$, this value coincides with $C_n = 0.2$ without DSM. Thus, the DSM system actuates as a small-size storage system. Moreover, the ξ increase carried out by the DSM is not constant and its benefits disappear as the battery capacity increase.

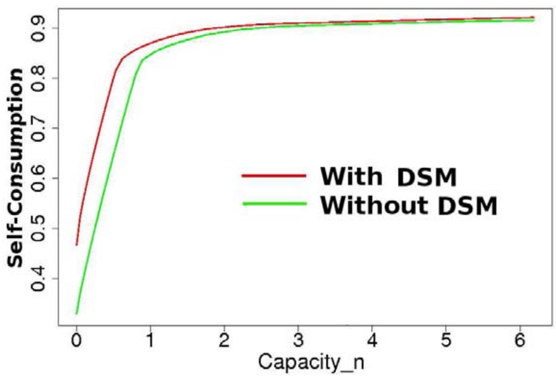


Figure 5: Relationship between ξ and normalized capacity for yearly studies.

C_n	ξ without DSM	ξ without DSM
0	0.328	0.468
0.2	0.468	0.626
0.5	0.638	0.794
0.8	0.806	0.858
1	0.85	0.871
3	0.91	0.915
∞	1	1

Table 1: Relevant ξ and C_n relation values.

5 REAL EXPERIMENT RESULTS

Real experiments have been performed between June and August 2010 in MagicBox to validate the battery controllers developed, as well as GeDELOS-PV system operation. Results of two weeks of uninterrupted operation of the house are summarised. Daily loads vary between 11 and 13 kWh and the storage capacity used was 5.4 kWh (C_n~0.5). Moreover, the PV generation has been limited to 5.55 kWp because the original one is high for a single house.

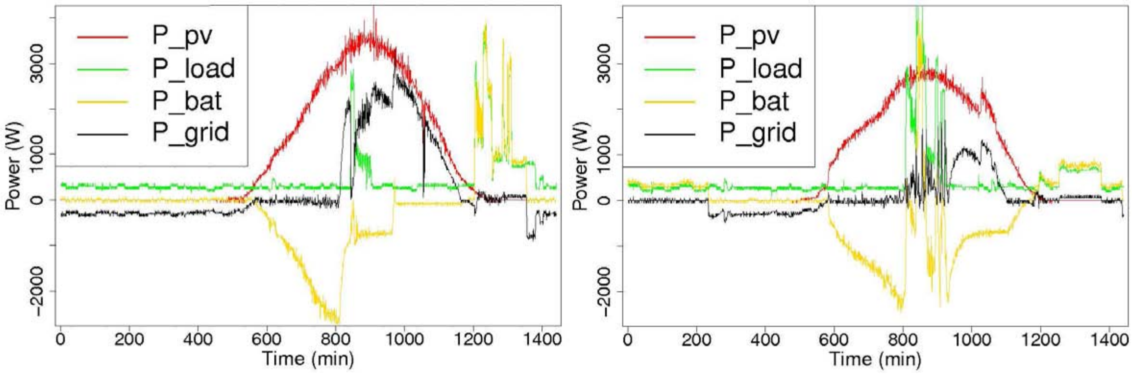


Figure 6: Power flows for measured experimental days: a) without DSM and b) with DSM.

Figure 6a shows the power flows on a day without DSM (only storage), where the loads are mostly concentrated at lunch-time and especially in the evening, when there is not PV generation (typical distribution of Spanish house). As it can be observed, the night loads are supplied from the grid and the batteries are charged only when the PV generation exceeds the local demand (recall that the batteries are only charged from the PV system or discharged to the loads). At lunch time (min. 800), an increase of demand modifies the battery operation mode, which changes to discharge in order to supply the sharp peak demand without importing electricity from the grid. After the peak demand the PV electricity is again able to supply directly the loads and the battery is again charged with the excess energy (constant power around 1 kW). In the evening, the battery is discharged to supply the evening loads until all PV electricity stored is exhausted. The system has achieved $\xi = 0.693$. Figure 6b shows another day with storage and DSM, where the deferrable load has been displaced in order to optimise the Self-Consumption of PV electricity. $\xi = 0.847$ has been achieved in this experiment. Table 2 includes the measured energy variable values for both example days. The values average throughout the experiments weeks has been also included.

	Day: storage only	Week: storage only [(1)]	Day: storage & DSM	Week: storage & DSM [(1)]
E_{load} (kWh)	11.974	10.818	12.569	11.788
E_{pv} (kWh)	22.392	22.887	18.684	23.149
$E_{pv,load}$ (kWh)	4.161	3.817	5.854	6.130
$E_{pv,bat}$ (kWh)	8.211	8.231	9.284	5.911
$E_{pv,grid}$ (kWh)	10.020	10.839	3.546	11.108
$E_{bat,load}$ (kWh)	4.139	3.819	4.790	3.642
ξ (%)	69.3	70.7	84.7	77.8

Note: (1) Daily averages.

Table 2: Daily and weekly results, ξ and energy variables.

6 CONCLUSIONS

An Active Demand Side Management system that combines new PV hybrid technology with Demand Side Management strategies has been presented, the "GeDELOS-PV" system. For the results presented in this paper the system has been configured to maximise the amount of PV electricity used on-site (self-consumption), either directly or indirectly through battery storage.

We have observed that the relationship between the electric energy flows and the capacity is not linear. As expected, the relationship between self-consumption factor and the capacity follows the same evolution. This relationship is an important design criterion, which involves that oversized storage does not produce relevant energy benefits with regard to the local energy optimization. The use of DSM strategies entails relevant advantages as:

- It reduces energy losses. A DSM system has not direct energy losses because there is not physical contact with the energy system. In the other hand, a storage system has different losses depending on the technology.
- It reduces the battery size and therefore the cost. A DSM system only needs to control electronics and depending on the devices the cost is low compared with a large storage system.
- It increases the energy management possibilities. By controlling the demand we can implement new energy strategies.
- With regard to the scalability, an increase of the demanded energy doesn't involve an increase of the DSM size, because it is a software controller.

As a general conclusion, the "GeDELOS-PV" system has demonstrated that the combination of small-scale storage with Demand Side Management significantly improves the local use of PV, thus increasing the PV value for the user. This combination will play an important role in future smart grids.

7 ACKOWNLEDGEMENT

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