SELF-CONSUMPTION OF PV ELECTRICITY WITH ACTIVE DEMAND SIDE MANAGEMENT: THE GEDELOS-PV SYSTEM

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ABSTRACT: An Active Demand Side Management system that combines new PV hybrid technology with Demand Side Management strategies has been presented: the “GeDELOS-PV” system. In this study the system has been programmed to maximise the amount of PV electricity used on-site (self-consumption), either directly or indirectly through battery storage. Simulations have been done of the Self-consumption achieved for different storage sizes, and experimental measurements have been also carried out in a prototype of self-sufficient solar house, with only storage and with storage and Demand Side Management Strategies. The results 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 the future smart grids.
Keywords: Demand-Side, Battery storage and control, Appliances and loads

1 INTRODUCTION

With rising prices of retail electricity and decreasing costs of PV, grid parity with commercial electricity will soon become a reality in the European Union. This fact, together with less attractive feed-in-tariffs for PV in the near future and incentives to promote self-consumption (existing in Germany since 2009 and currently under discussion in Spain) suggest that new operation modes for PV Distributed Generation should be explored, different from the traditional approach based on maximizing the electricity exported to the grid. An example of alternative approach is to integrate the user demand and local PV generation patterns, so that an optimal use of PV electricity can be achieved, either directly or indirectly (through storage, deferred for later use). In this way, not only a higher efficiency in energy use is achieved; economic benefits can be also expected, for example, in regulatory frameworks with time-dependent electricity tariffs, typical of liberalised electricity markets.

2 ACTIVE DEMAND SIDE MANAGEMENT

Demand-Side Management (DSM), defined here as actions that influence the way consumers use electricity in order to achieve savings and higher efficiency in energy use [1], has been identified as one of the main strategies to be promoted in order to guarantee security of supply in the European Union [2]. 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).

Residential consumers could be the first to benefit from ADSM strategies, provided that technologies exist that facilitate (automate) the task without compromising the users comfort needs and preferences. Currently, DSM is increasingly viable by means of highly efficient electrical appliances that can be remotely controlled [3]. However, to perform a true ADSM several challenges must be faced up:

- From a PV engineering perspective, supervision and management are necessary to know in real-time the status of the PV system components, as well as to forecast the expected generation in a short time scale (for example, on a 24-hour basis).
- From a Control engineering perspective, loads management should be able to deal with many parameters and variables influencing the consumption pattern (related to the user preferences and electrical appliances). In addition, it should also consider information coming from the local sources (PV and storage) and the grid (price signals, remote commands, etc.).

These challenges have inspired the project “Residential electricity demand side management with PV technology” (GEDELOS-PV), carried out by several departments and institutes of the Technical University of Madrid. In this paper we will demonstrate the possibilities of ADSM strategies to optimise the local use of PV electricity.

2.1 The Self-consumption Factor

Figure 1 shows a block diagram of a PV hybrid system installed in a grid-connected building, where 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_l respectively) indicate the positive sign criteria adopted.

In order to optimise the local consumption of PV electricity, either immediately or deferred over time through local storage, the batteries operation is set independent of the grid. This means that batteries are not allowed to be charged from the grid, nor be discharged to the grid.

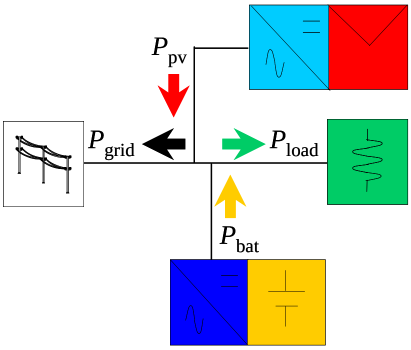


Figure 1: Block diagram of PV hybrid system installed in a grid-connected building

The following equations apply to the electricity flows (energies) of interest within the system:

- For the PV electricity, E_{pv}:

$$E_{pv} = E_{pv,load} + E_{pv,bat} + E_{pv,grid} \qquad (1)$$

where $E_{pv,load}$, $E_{pv,bat}$ and $E_{pv,grid}$ are PV electricity feeding the loads, stored in the batteries and fed into the grid, respectively.

- For the PV electricity stored in the batteries, $E_{pv,bat}$:

$$E_{pv,bat} = E_{bat,load} + E_{bat(SoC)} - E_{bat(SoC,0)} \quad (2)$$

where $E_{bat,load}$ is the electricity extracted from the batteries, and $E_{bat(SoC)}$ is the electricity stored at the end of the analysed period (function of the batteries State of Charge, SoC), and $E_{bat(SoC,0)}$ is the electricity stored at the beginning of the period.

- For the loads demand, E_{load}:

$$E_{load} = E_{pv,load} + E_{bat,load} + E_{grid,i} \qquad (3)$$

where $E_{grid,i}$ is the electricity imported from the grid.

The fraction of load that is supplied (directly and indirectly) from the PV system, or Self-consumption factor ξ is:

$$\xi = \frac{E_{pv,load} + E_{bat,load}}{E_{load}} \qquad (4)$$

It should be noted that the proposed factor can be used in different time-frames. In addition, the fact that it is normalised (divided) by the loads demand allows comparing the Self-consumption of PV systems with different sizes and loads. Since the direct and indirect local use of PV production ultimately depend on the demand, it can be concluded that $\xi \in [0,1]$. ($\xi=0$ would be the case of a building with no local generation available, and $\xi=1$ the case of a building with an autonomous — physically or functionally— PV system).

3 GEDELOS-PV SYSTEM

3.1 General description

GEDELOS-PV is an ADSM system that integrates PV hybrid and Loads Control technologies in order to displace the consumer's load curve in response to local (solar irradiation, storage availability, user preferences) and external conditions (distribution grid) [4]. It has been developed on a prototype of self-sufficient solar house called "MagicBox", consisting of a 7 kWp PV generator 7.7 kW of grid-connected inverters, 72 kWh of electrical storage (stationary lead-acid batteries), a 5 kW battery inverter, a small meteorological station (irradiance and ambient temperature measurements), datalogging facilities and electricity meters. The house also includes electrical appliances typical of a highly electrified home (washing machine, dryer, dishwasher, refrigerator, vitroceramic cooking range, oven, air conditioning, lighting, audiovisual appliances). The most consuming ones (kitchen and laundry appliances) can be remotely controlled using Information and Communication Technologies and are considered "deferrable" loads, in contrast with the "non deferrable" ones that will be used whenever the user needs or desires (e.g.: lighting, TV, etc).

Besides the previously described hardware, GeDELOS-PV system also includes software tools that supervise the operation of its components and control the battery inverter and deferrable loads. Several improvements have been introduced in the first version presented previously at this conference [4]:

- At the Supervision level, a Predictions block has been developed that provides estimates of the hourly PV generation on a 24 hour basis, based on forecasts of solar irradiation and ambient temperature provided by the Spanish Meteorological Agency [5], together with models that take into account the particular characteristics of the PV system components.
- At the Loads Control level, the control of the house is carried out by a combined distributed-centralised planner, shown in Figure 2. The distributed planner is divided into "agents", where each agent represents one appliance and the associated database with information about electricity consumption in different operation modes (e.g. washing machine program and input water temperature) is stored. Each agent produces a planning according to the user needs and preferences, PV system components status and predictions of the expected PV generation. The centralized planner or Coordinator receives all agents' planning and decides the one to be executed according to GeDELOS-PV system objectives, in this study, maximization of the Self-consumption factor in power and energy terms. Also, the Coordinator sends the corresponding commands to the loads.
- Of particular interest is the battery control, which determines the use indirect use of PV electricity. In this sense, several high-level (software) battery controllers have been developed and tested [6], by making use of the available current controllers of the battery inverter. The one that performs best in terms of maximising ξ defines the following states depending on the battery SoC (see also Figure 3):
  - Overcharge (OC): whenever SoC(%)≥95. The battery supplies the loads and the battery controller regulates the charging process by means of a specific function that controls dynamically 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.

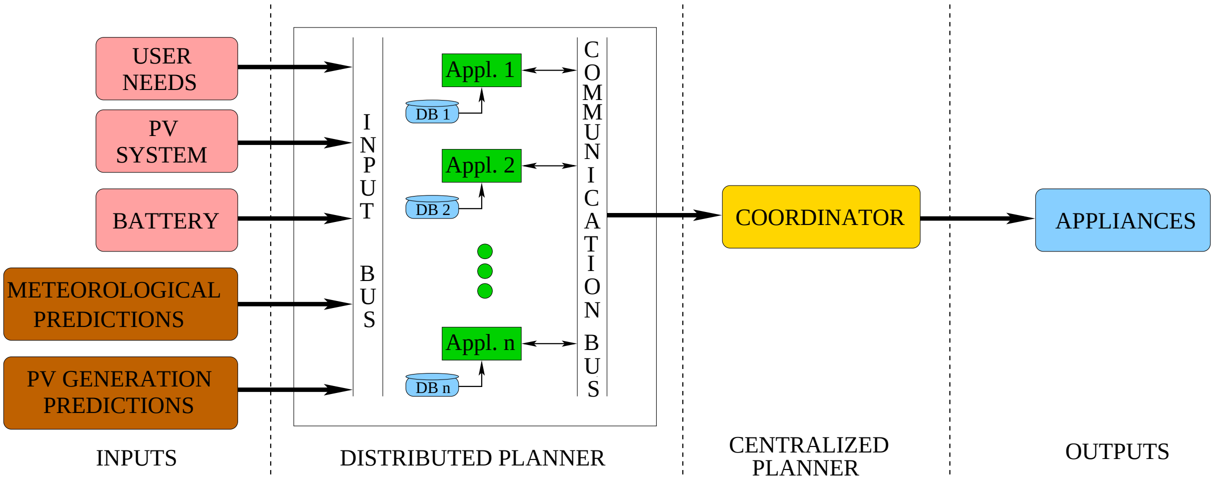


Figure 2: Block diagram of GEDELOS-PV Loads Control

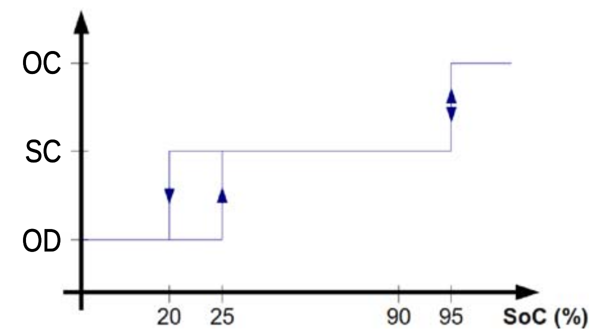


Figure 3: Battery controller states (OC, Overcharge; SC, SelfConsumption; OD, Overdischarge)

- Self-Consumption (SC): if 25<SoC(%)>95. Grid-connection is physically maintained, but interchanges of electricity with the grid are minimised.
- Overdischarge (OD): whenever SoC(%)<20. The battery ceases supplying the loads, battery charging is only allowed whenever PV generation exceeds loads demand.

3.2 Simulation results

Simulations have been performed using one-year data of actual PV generation of (from 14/7/2009 until 13/7/2010) as input to GeDELOS-PV system. As load pattern, a constant daily consumption of about 11.5 kWh has been considered, its daily distribution being typical of a small-size family in Spain (see Figure 6a). In daily terms, 22% of daily consumption is considered "deferrable", related to the washing machine, dryer and dishwasher. Also, in order to consider a PV generator that produces roughly the annual consumption, the original PV data have been filtered, equivalent to having an installed PV power of 5.6 kWp (1.4 kWp less than the original 7 kWp) and annual generation of 5.71 MWh.

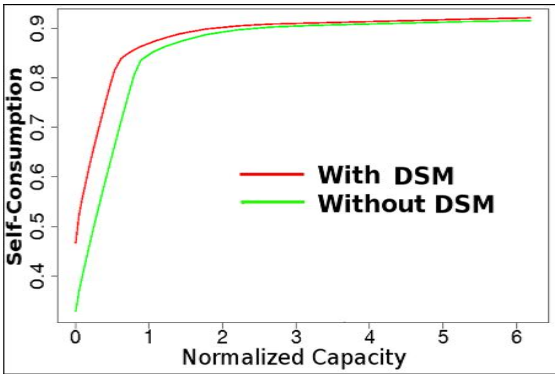


Figure 4: Self-consumption *versus* normalised capacity C_n (annual results)

Figure 4 summarises the annual simulation results, by showing the evolution of Self-Consumption factors of PV homes with and without Demand Side Management strategies (red and green curves respectively), for different storage capacities. The storage capacity is defined in normalised terms ("normalised capacity") with respect to the daily load:

$$C_n = \frac{C_{bat}\ (kWh)}{E_{load}\ (kWh)} \qquad (5)$$

Several aspects are worth mentioning:

- In both cases a first region of small-scale storages can be identified (equivalent to less than 1 day of autonomy), for which a fast, almost linear growth rate of ξ exists with increasing capacity. For large capacities (especially C_n>2) both curves seem to saturate. In the transition between the two regions lies a maximum capacity that should not be exceeded, for good engineering practice purposes.
- With no DSM nor storage capacity (C_n=0) the Self-consumption factor is limited to the simultaneity of PV generation and load patterns, in this study ξ=0.33 (or 33%). Adding DSM strategies would increase the factor by 42%, to ξ=0.47. By comparing both results it can be stated that DSM would be equivalent to a local storage of 2.2 kWh (C_n=0.19).

- With DSM combined with storage the improvements in the Self-consumption factor are more important with small storage capacities than with larger. This is because a large capacity allows the PV electricity to be deferred many hours and, therefore, be indirectly used on-site. The limited amount of deferrable loads used in this study (22%) consequently limits the influence of DSM in overall PV Self-consumption.

The annual results obtain mean that in the winter period the Self-Consumption of PV will be lower and in the summer one larger. Figure 5 shows the evolution of ξ with the storage capacity for the months of January, April, July and October.

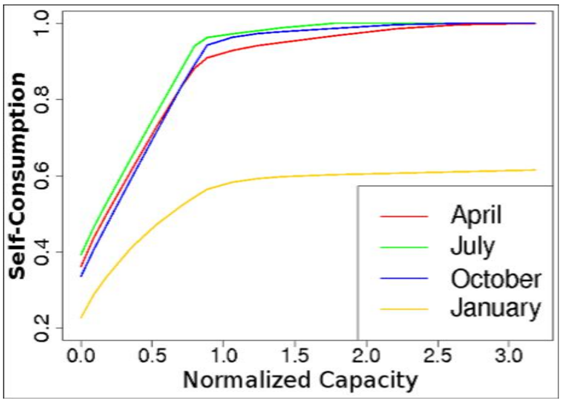


Figure 5: Self-consumption *vs.* normalized capacity C_n (monthly results)

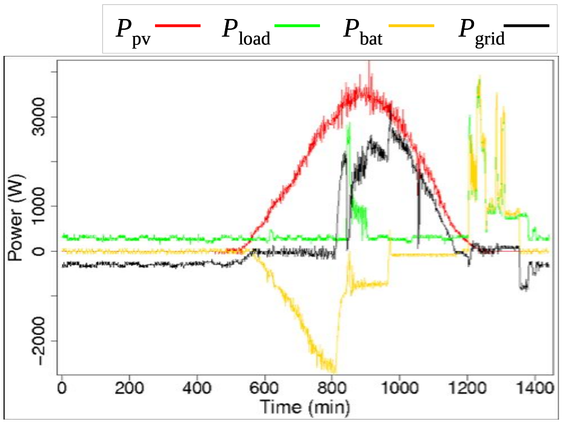
3.3 Experimental results

Experimental measurements have been performed between June and August 2010 to validate the battery controllers developed, as well as GeDELOS-PV system operation. In this section the results of 2 weeks of uninterrupted operation of the house (PV hybrid system + loads + GeDELOS-PV) are summarised. Daily loads varied between 11 and 13 kWh and the storage capacity used was 5.4 kWh (C_n~0.5). All power variables have been measured every minute.

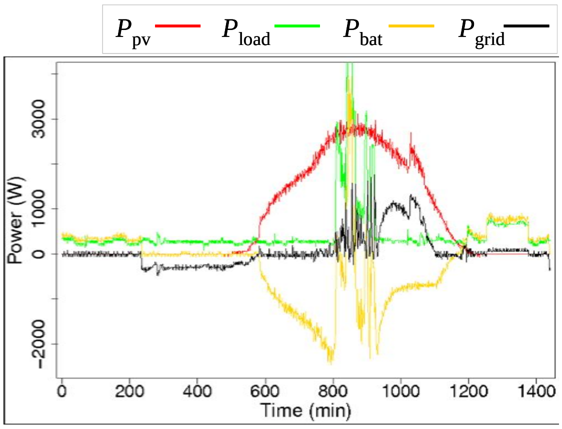
Figure 6(a) shows the power flows on a day without DSM strategy (only storage), where the loads are mostly concentrated at lunch-time and especially in the evening (from 20:00 h. on), when there is almost no PV generation. As it can be seen, the night loads are supplied from the grid and the batteries start being charged only when PV generation exceeds the local demand (remember that the batteries are only charged from PV or discharged to the loads). At lunch time (min. 800) a rapid 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 to the loads and the battery is charged again with the excess (constant power around 1 kW). In the evening the battery is discharged to supply the evening loads until all PV electricity stored is used up.

Figure 6(b) shows another day with storage and DSM, where the deferrable load has been displaced in order to optimise the Self-Consumption of PV electricity. In this case the batteries are used at the beginning of the night to supply the existing load until the stored PV electricity of the previous day has been used. Then the batteries start being charged with the excess of PV power until lunch time, when the rapid increase of the demand occurs (not only are cooking appliances used, but also deferrable appliances) and the stored PV electricity is used to complement the existing PV generation in order to supply the demand without importing electricity from the grid. When the loads decrease below PV generation the excess is again stored in the batteries until the evening, when it is used to supply the evening loads.

Table I shows the numerical results of the main energy variables and Self-consumption factor ξ, for both days explained and the average daily results of the two weeks.



(a) Only storage (28/7/2010)



(b) With storage and DSM (30/8/2010)

Figure 6: Power flows in two example days (see Figure 1 for positive sign criteria of power variables)

Table I: Daily and weekly results: Self-consumption ξ and characteristic parameters

	Day: storage only	Week: storage only (1)	Day: storage & DSM	Week: storage & DSM (1)
E_{load} (kWh)	11.974	10.990	12.569	11.734
E_{pv} (kWh)	22.392	23.450	18.684	23.215
$E_{pv,load}$ (kWh)	4.161	3.866	5.854	5.618
$E_{pv,bat}$ (kWh)	8.211	8.076	9.284	6.460
$E_{pv,grid}$ (kWh)	10.020	11.101	3.546	8.349
$E_{bat,load}$ (kWh)	4.139	4.060	4.790	3.734
ξ (%)	69.3	72.1	84.7	75.9
$L_{storage}$ (kWh)	4.074	3.954	4.402	3.494
(%E_{pv})	18.2	17.2	23.6	18.0
$L_{inv,bat}$ (kWh)	0.899	0.856	1.303	0.939
(%$L_{storage}$)	22.1	21.7	30.0	32.2

Note: (1) Daily averages.

Note that the Self-consumption results of the days where only storage was used (no DSM, first 2 columns of the table) are coherent with the Self-consumption line shown in Figure 5 for the typical summer months (July in the figure).

In the lower part of Table I also the losses due to the storage system (batteries + battery inverter) are shown, in kWh and as percentage of the PV electricity produced. In addition, losses due to the battery inverter are shown in kWh and as percentage of the storage losses.

As it can be seen, losses of the storage system were between 17 and 24% of the PV electricity produced. The authors think that these values can be reduced, because the battery operated much of the time near the overcharging zone, where the battery efficiency is rather low. Changes in the battery controller will be introduced in the future, in order to force the battery to operate well below the overcharging zone.

5 FINAL REMARKS AND 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. In this study the system has been programmed to maximise the amount of PV electricity used on-site (self-consumption), either directly or indirectly through battery storage.

Simulations have been done of the Self-consumption factor for different storage sizes, showing that beyond 1 day of autonomy (Normalized capacity C_n>1) increases of the Self-consumption tend to saturate, which means that increasing the capacity above such limit does not lead to relevant improvements of the Self-consumption.

Experimental measurements have been also carried out in a prototype of self-sufficient solar house along two weeks, one with only storage and another one with storage and Demand Side Management Strategies. It has been demonstrated that DSM clearly improves the Self-consumption of PV electricity and, indeed, can be considered as a small-size storage system (in this case, equivalent to a normalized capacity of 0.2, or 20% of the daily load). Other advantages of DSM are that it reduces the battery size needed to achieve a certain degree of Self-consumption, increases energy management possibilities and allows an easy scalability (i.e., it can manage different powers without the need to change any hardware). Further research will be done in "GeDELOS-PV" system in order to improve the energy behaviour as well as study new system objectives such as optimisation of PV local use according to different electricity prize scenarios (for example, under time-of-use tariffs).

As a general conclusion, through "GeDELOS-PV" system it has been 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 the future smart grids.

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7 REFERENCES

[1] J.I. Pérez Arriaga, L.J. Sánchez, M. Pardo, "La gestión de la demanda de electricidad" (in Spanish), Ed. Fundación Alternativas, Madrid (2005).
[2] European Commission, "Towards a EU strategy for the security of energy supply", COM (2002) 321, 2002.
[3] M. Hinnells, "Technologies to achieve demand reduction and microgeneration in buildings". Energy Policy 36 (2008) 4427.
[4] E. Caamaño-Martín, D. Masa, A. Gutiérrez, F. Monasterio, M. Castillo, J. Jiménez-Leube, J. Porro, "Optimizing PV use through Active Demand Side Management". Proceedings 24th European PV Solar Energy Conference (2009), pp. 3149-3155, Hamburg.
[5] D. Masa-Bote, E. Caamaño-Martín, "Forecast of energy production for PV systems 24 hours ahead". In this conference.
[6] M. Castillo, "Optimización del uso de tecnología fotovoltaica en entornos residenciales" (in Spanish), Trabajo Fin de Master, E.T.S.I. Telecomunicación (2010), Universidad Politécnica de Madrid.