OPTIMIZING PV USE THROUGH ACTIVE DEMAND SIDE MANAGEMENT

E. Caamaño-Martín[(1)*], D. Masa[(1)], A. Gutiérrez[(2)], F. Monasterio[(2)], M. Castillo[(2)], J. Jiménez-Leube[(3)], J. Porro[(1)]

[(1)] Instituto de Energía Solar, Av. Complutense 30, 28040 Madrid, Spain (Ph: +34.91.5441060; Fax: +34.91.5446341)

[(2)] Dpto. Tecnologías Especiales Aplicadas a la Telecomunicación, ETSI Telecomunicación, Av. Complutense 30, 28040 Madrid, Spain (Ph./Fax: +34.91.3367278)

[(3)]Dpto. Tecnología Electrónica, ETSI Telecomunicación, Av. Complutense 30, 28040 Madrid, Spain (Ph: +34.913367219; Fax: +34.913367216)

[*] Corresponding author, e-mail: estefan@ies-def.upm.es

ABSTRACT: With 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. An example can be found in the domestic sector, where the use of modern PV hybrid systems combined with efficient electrical appliances and demand side management strategies can significantly enhance the PV value for the user. This paper presents an active demand side management system able to displace the consumer's load curve in response to local (PV hybrid system, user) and external conditions (external grid). In this way, the consumer becomes an "active consumer" that can also cooperate with others and the grid, increasing even more the PV value for the electrical system.
Keywords:"Small Grid connected PV systems", "Energy Performance", "Battery Storage and Control"

1 INTRODUCTION

The growing penetration of Distributed Generation (DG) technologies in electricity networks has arisen the need to guarantee that these technologies are effectively integrated and not just connected (appended) to the networks. Photovoltaics, although behind other technologies (namely wind) in terms of installed capacity, is currently the most important DG technology using inverters to convert the primary DC current into AC. This fact, together with its rapid penetration in distribution networks within the framework of successful regulatory state and marketing programmes makes PV-DG worthwhile to be considered in planning and operation of present and future electricity networks.

As it is well known, integration of PV-DG can bring benefits to electricity systems, both in instantaneous terms (reductions of losses, peak-loads and environmental impacts) and in the medium-long term (deferral of future capacity investments), which can be maximized if PV systems are deployed at or close to electricity consumption points. Traditionally, due to the inherent uncontrollable characteristics of the solar resource, network operators have hesitated to rely on PV as a firm capacity component. However, recent technological developments in power conditioning systems enable nowadays a true dynamic interaction between PV systems and the networks, thus increasing the PV value [1,2].

These added-values of PV technology have been, however, very little explored up to now. In fact, most successful feed-in-tariffs for PV clearly exceed the price of commercial electricity; as a consequence, the majority of PV systems are operated focusing on maximization of the "exported" electricity to the public grid above other operation modes. However, with rising prices of retail electricity and decreasing costs of PV, grid parity with residential electricity has been predicted to become a reality in the next decade in the European Union [3]. This fact, together with less attractive feed-in-tariffs in the future and/or other incentives to promote self-consumption (such as the one introduced in Germany for PV systems under 30 kW built in 2009 [4]) call for new operation modes for PV systems that may be more beneficial for the PV owners than the traditional "all-feed-in".

2 ACTIVE DEMAND SIDE MANAGEMENT WITH PV TECHNOLOGY

A clear example of PV added value is the result of combining modern hybrid PV technology with Demand Side Management strategies in the residential sector:

- The PV systems combine grid connected-type inverters with small-scale electricity storage and an active control of the grid interface, thus giving the possibility to operate in a grid connected or isolated mode [5].
- Demand Side Management —defined here as actions taken to influence the way consumers use electricity to achieve energy savings and higher efficiency in energy use— of residential consumers is increasingly viable with the use of highly efficient electrical appliances that can be remotely controlled [6].
- Through the control of local loads, PV electricity can enhance its value by being locally consumed or fed into the grid, depending on different factors (power/energy related, economic, user's preferences, etc.). In this way, the PV owner becomes an active consumer that can optimize its PV system as well as cooperate with others and the grid.

The real integration of the previous concepts entails that the strategies used to manage the loads should consider, besides the user's demands, the local availability of electricity (coming from the PV modules, storage or the grid) as well as other external factors (for example, "signals" indicating the hourly prices of retail electricity) that may determine the electricity consumption pattern. Without doubt there are several challenges that must be faced up to attain such objective:

- From a PV engineering perspective, supervising and management systems are necessary to know in real-time the status of the PV system, to predict the expected PV generation in a short time scale, as well as to respond to external signals coming from the

user or the grid (telecommands, etc.).

- From the Control engineering perspective, the loads management needs to consider many parameters and variables influencing the consumption pattern (related both to the user and electrical appliances) and, therefore, to process a lot of information in an intelligent way. In addition, it must incorporate information from the local electricity sources (PV and storage) and the grid (prices, etc.).

These and other 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, the first results of which are presented in this paper.

3 THE "GEDELOS-PV" SYSTEM

GEDELOS-PV system is an electricity Demand Management System integrated with PV technology able to displace the consumer's load curve in response to local (solar irradiation, storage availability, user preferences) and external conditions coming from the distribution network. Figure 1 shows a block diagram of the system, composed by the PV and Control systems, together with the loads, associated sensors and the elements that may interact with the system (the user and the grid).
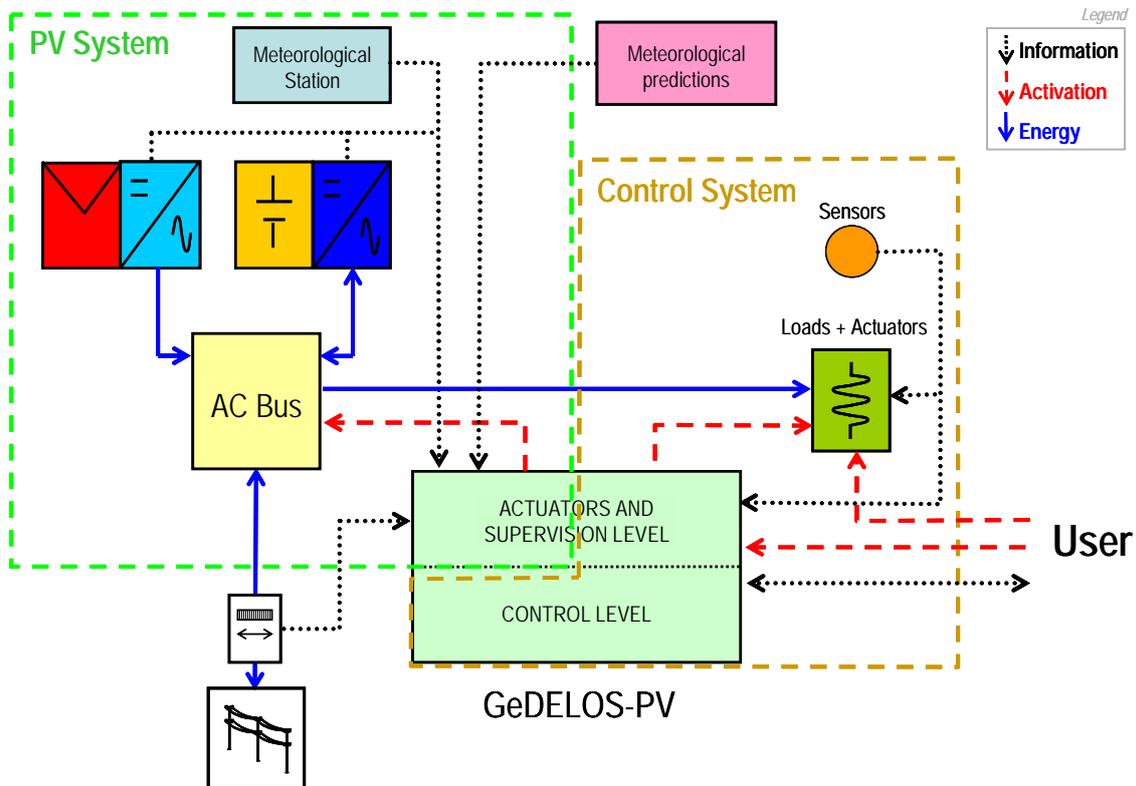
Figure 1: Blocks diagram of GEDELOS-PV system

Blue arrows indicate the power/energy flows between the different elements capable of producing electricity (PV generators, storage and the grid) or consume it (loads, storage and the grid). Black arrows show how these elements exchange information: the system receives data from all elements and provides information to the actuators (distributed control of the loads) and the user. Finally, red arrows show the flow direction of the actuation commands: GEDELOS-PV system is responsible of acting upon all elements in parallel with the user demands, which are given the maximum priority and can be transmitted through the system or directly to the loads.

The main characteristics of the PV system are the following:
- 6 Independent PV generators (7 kWp) of monocrystalline Silicon technology manufactured by Isofoton, distributed in 4 different south-oriented surfaces (tilt degrees of 12º, 25º, 39º and 90º).
- A power conditioning system based on AC coupled

principles, consisting of 6 string-type inverters (total nominal power 7.7 kW) and 1 battery inverter (nominal power 5 kW), all of them manufactured by SMA Technologie AG.
- A lead-acid battery bank of 72 kWh (1500 Ah at 48 V nominal, stationary type batteries) manufactured by Enersys.
- Monitoring equipment comprising a small meteorological station (measuring irradiance on the 4 PV surfaces, ambient temperature and relative humidity) and data-logging facilities.

The system is located in a prototype of self-sufficient electricity house called "Magic Box" [7] that includes typical electrical appliances of a highly electrified home: washing machine, dryer, dishwasher, refrigerator, vitroceramic cooking range, oven, air conditioning, lighting, and small appliances. The most consuming (kitchen and laundry appliances) are manufactured by Siemens under the "Serve@Home" mark and can be locally or remotely controlled using Information and

Communication Technologies.

4 PV SYSTEM CHARACTERISATION RESULTS

Figure 2 shows the electrical configuration of the local grid (inside the house) in the grid-connected operation mode of the PV system, in which the PV electricity is fed through a specific branch independent from that of the loads. (In the autonomous operation mode connections are modified so that PV electricity is fed directly to the loads branch). The arrows shown next to the power variables of the PV system, batteries, grid and loads (P_{pv}, P_{bat}, P_{grid} and P_l respectively) show the sign criteria to be used in the following graphs, so that $P_{grid}>0$ means net imports of electricity from the public grid ($P_{grid}<0 \Rightarrow$ exports) and $P_{bat}>0$ discharge of the batteries ($P_{bat}<0 \Rightarrow$ charge).
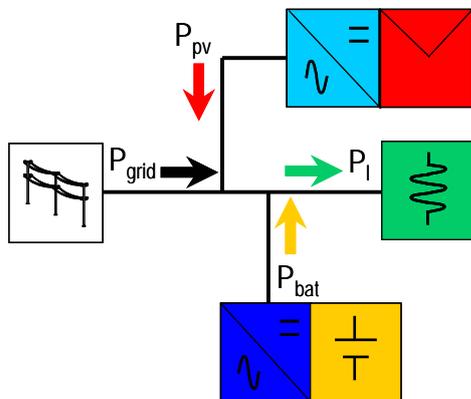
Figure 2: Local grid configuration (grid-connected mode)

Figure 3 shows an example of operation on a typical sunny day (represented data are 5 minutes averages of measured values every 1 minute), where PV generation extends between 9 and 20:30 h. (red line) and the main loads (green line, gathered in 3 groups: washing machine + oven, dryer + vitroceramic cook range, and finally dishwasher) are distributed between 12 and 18 h. As it can be seen, PV electricity first meets the loads and only exports to the public grid the excess generation ($P_{grid}<0$). Throughout the PV generation period only during a short interval (between 12:15 and 12:25 h.) loads demand exceed PV generation, from which a maximum power of 0.6 kW has to be imported from the grid. In daily terms, the local demand of 11.8 kWh is met by the PV strings and the grid by 69.8% and 30.2% respectively. The batteries are not used.

The next 2 figures show examples of battery use to help the PV system user to meet most of his/her electricity demand locally (from the PV system and the storage), without disconnecting from the grid.

In Figure 4 the battery inverter is programmed so as to meet the loads demand from 19 h. on (mainly oven + vitroceramic cook range to prepare dinner), when PV generation is relatively small. Interestingly, the fast dynamic response of the battery inverter allows the PV hybrid system to fulfil successfully the desired objective, without importing electricity from the grid.
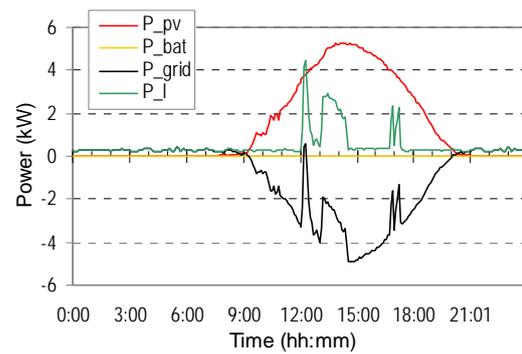
Figure 3: Day 1 - Conventional grid connection mode (no batteries)
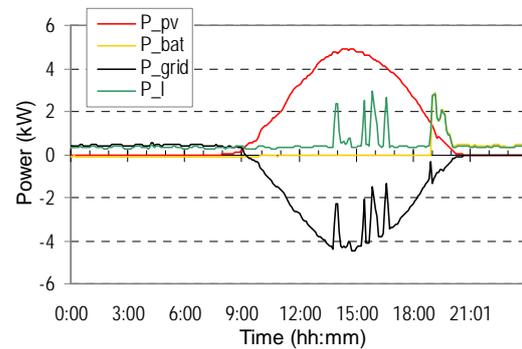
Figure 4: Day 2 – Grid connection + Battery discharge

Figure 5 shows the next day, in which the battery has continued supplying the loads demand up to 10 h. (batteries State of Charge decreased from 100% at 19 h. on the previous day to 89% at the end of the discharge period). From that time on the battery inverter is programmed to enter into the charging mode, up to 11:20 h. from PV and the grid, from 11:20 to 16:20 h. from the PV system only (battery SOC~100% at the end of this period) and from then on from the grid again (floating charge, very low charge current). Again, the fast dynamic response of the PV hybrid system can be seen between 15:40 and 15:50 h., when the local demand increases sharply (time coincidence of the dishwasher –following lunch time– and dryer) and the inverter battery changes its operation mode into battery discharge: once the peak load has disappeared the battery enters into the charging mode again.

In daily terms the local demand (12 kWh) was supplied, in day 2, by the PV strings, batteries and the grid in a 46.4%, 27.4% and 26.2% respectively. In day 3 the contributions are even higher for the PV strings and batteries (48.6% and 29.3% respectively) and consequently lower for the grid (22.1%). The use of the battery can, therefore, help to reduce the net demand from the grid during a pre-programmed period (starting from just a few minutes to several hours, depending on the storage availability), besides providing a way to store PV electricity at times when it is not locally consumed.
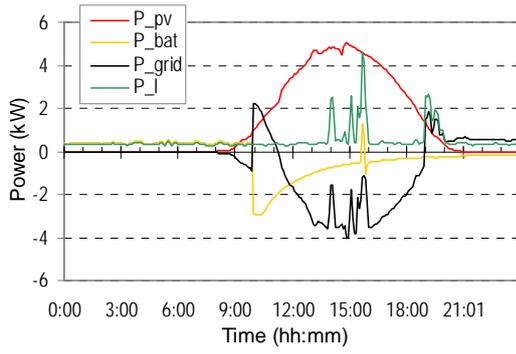
Figure 5: Day 3 – Grid connection + Battery discharge and charge

4.1 New characteristic parameters

In order to properly identify the electricity flows within the local grid (consumer's grid), conventional PV performance parameters for grid-connected systems like Final Yield are clearly insufficient. To this aim, the following parameters are proposed:

- To account for the end-use of PV strings electricity:

$$P_{pv} = P_{pv,l} + P_{pv,bat} + P_{pv,grid} \qquad (1)$$

being $P_{pv,l}$, $P_{pv,bat}$ and $P_{pv,grid}$ the PV electricity used to meet local loads demand, charge the batteries and public grid feed-in, respectively. From normalizing (dividing) the previous equation by the nominal power of the PV generators (P_{nomG}) the following characteristic parameters result:

$$Y_f = Y_{f,l} + Y_{f,bat} + Y_{f,grid} \qquad (2)$$

- To account for the end-use of electricity stored in the batteries a "Battery use factor" is proposed [8]:

$$F_{bat} = \frac{P_{bat}(>0)}{P_{nomG}} \qquad (3)$$

with P_{bat} being the power extracted from the battery under dicharge operation mode ($P_{bat}>0$). This factor can be splitted into 2 factors accounting for the end-use of the stored electricity by the local appliances and the grid:

$$F_{bat} = F_{bat,l} + F_{bat,grid} \qquad (4)$$

- Finally, to account for the end-use of grid electricity a "Grid use factor" is proposed:

$$F_{grid} = \frac{P_{grid}(>0)}{P_{nomG}} \qquad (5)$$

with P_{grid} being the power imported from the grid ($P_{grid}>0$). Again, this factor can be splitted into 2 ones accounting for the end-use of the grid electricity by the local appliances and the batteries:

$$F_{grid} = F_{grid,l} + F_{grid,bat} \qquad (6)$$

The reasoning behind the definition of these parameters is the possibility to compare the battery and grid uses with the available PV electricity in normalized terms (hours equivalent of PV generation). As well as with the conventional PV performance parameters, they can be evaluated in instantaneous (power) or integrated terms (energy). Figure 6 shows as an example the hourly values corresponding to day 3, the one with most varying energy exchanges.
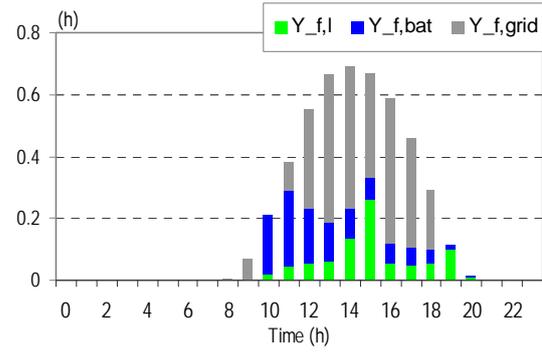
(a) End-use of PV strings electricity
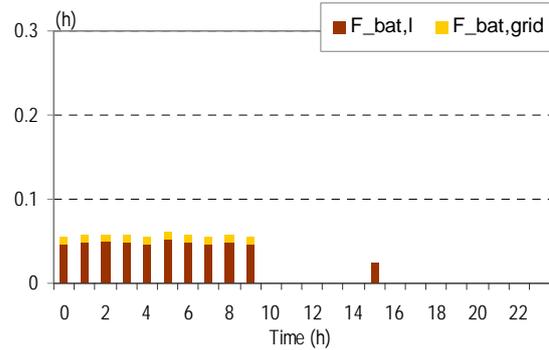
(b) End-use of batteries stored electricity
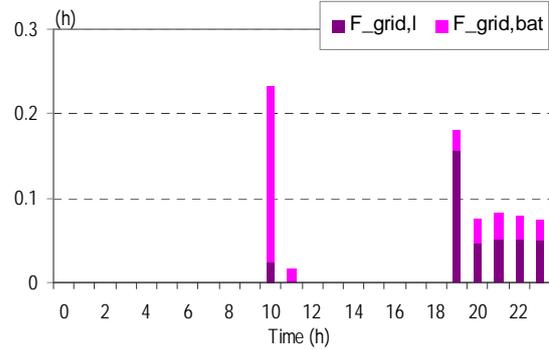
(c) End-use of grid electricity

Figure 6: Day 3 - Hourly characteristic parameters

As it can be seen, the hourly use of both the batteries and the grid represent just a small fraction of an equivalent hour of PV generation. The next table shows the daily values of the characteristic parameters of the 3 days analyzed; in brackets, the percentage distribution of Y_f, F_{bat} and F_{grid} is also indicated.

Table I: Daily values of characteristic parameters

	Day 1 (h)	Day 2 (h)	Day 3 (h)
Y_f	4.970 (100%)	4.629 (100%)	4.688 (100%)
$Y_{f,l}$	1.179 (23.7%)	0.793 (17.1%)	0.841 (17.9%)
$Y_{f,bat}$	0 (0%)	0.087 (1.9%)	1.086 (23.2%)
$Y_{f,grid}$	3.791 (76.3%)	3.749 (81.0%)	2.762 (58.9%)
F_{bat}	0 (100%)	0.513 (100%)	0.598 (100%)
$F_{bat,l}$	0	0.469 (91.5%)	0.506 (84.7%)
$F_{bat,grid}$	0	0.044 (8.5%)	0.092 (15.3%)
F_{grid}	0.511 (100%)	0.556 (100%)	0.741 (100%)
$F_{grid,l}$	0.511 (100%)	0.449 (80.7%)	0.382 (51.6%)
$F_{grid,bat}$	0 (0%)	0.107 (19.3%)	0.358 (48.4%)

From the comparison of results of days 2 and 3, the direct use of PV electricity to meet the house demand is comparable. In day 3, however, 23% of PV electricity is used to charge the batteries, thus compensating the previous discharge from the evening of day 2 till the morning of day 3). The use of the stored electricity in the batteries is also slightly more evenly distributed between the loads and the grid (although no specific objective to export electricity to the grid was established), which shows the possibility of the PV hybrid system to export electricity to the public grid, if necessary (for example, upon demand of the grid operator). Concerning the use of the grid electricity, in day 3 it is also more evenly distributed between the loads and the battery than in day 2. This last use could be reduced if the user planned his loads pattern in a way so as to charge the battery predominantly with PV electricity, for example, by delaying the beginning of the battery charge until 12 h., when the PV generation (P_{pv} ~3.5 kW) is able to meet both the existing loads and the battery power demand (P_l ~0.4 kW and P_{bat} ~3 kW respectively). This task is to be performed by the Control system of GEDELOS-PV, as it is explained next.

5 CONTROL ARCHITECTURE

The Control system has been developed based on a distributed architecture (see Figure 7), in which the different sub-systems (associated to each load) obtain the user's information and the estimated consumption for each appliance. Each subsystem implements an intelligent control structure, which creates a global planning to satisfy the user's needs. To achieve this scheduling each sub-system makes use of its consumption estimations as primary information and the others estimations as secondary information. These planning are transmitted to a Coordinator that creates a global action plan based on the user's needs, local (PV system) and external conditions (grid). The Coordinator main objective is to maximize the performance in terms of power and energy.
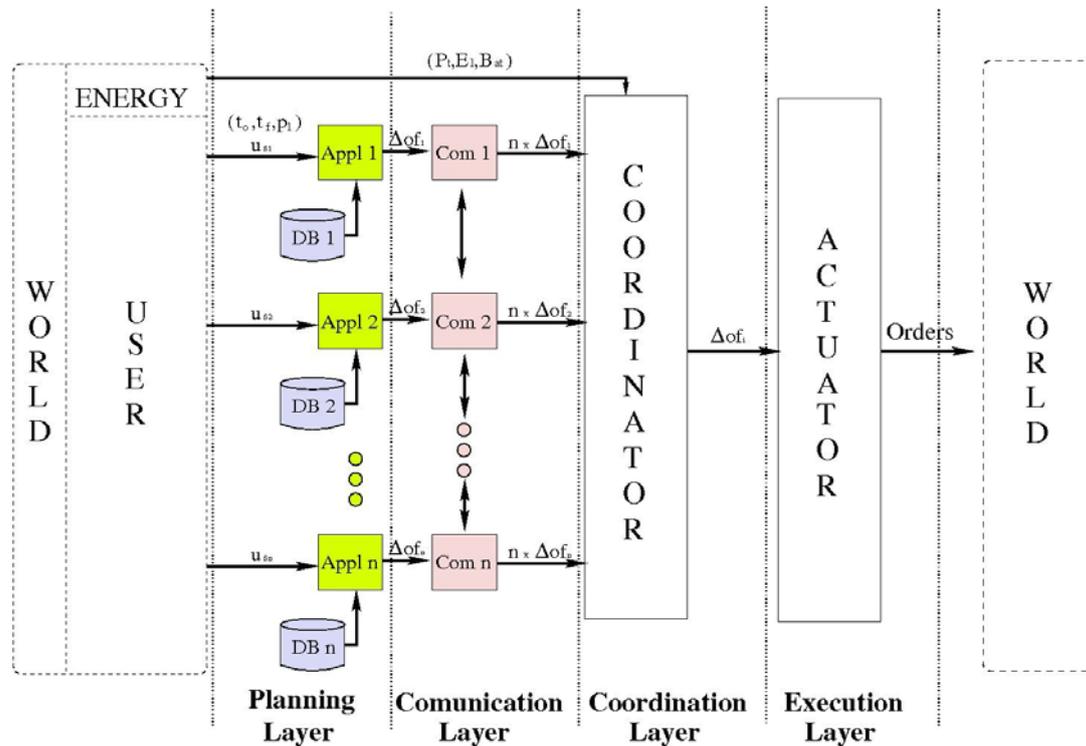
Figure 7: Blocks diagram of the Control architecture

The architecture is divided in two main blocks: one distributed and one centralized. In the distributed block, each subsystem associated to a load receives information from the user needs (e.g., the washing machine must be finished before 16:00 h. with a fixed temperature and revolutions program). Therefore, each appliance obtains information about the estimated consumption from its data base and tries to schedule it in the temporal axis (Planning layer). After that, each appliance communicates its orders to the rest of the sub-systems, scheduling everyone's needs inside this axis. After a number of interactions, each appliance has created a different planning, in which it takes into account not only its needs, but all the loads (Communication layer). Once this stage is finished, each subsystem sends its planning to the centralized block. The Coordinator (Coordination layer) then selects the better scheduling taking into account the batteries storage, the expected PV generation (predictions based on hourly global irradiation data provided by the Spanish Meteorological Agency, see pink box on Figure 1) and the grid (state, electricity prices). Furthermore, the coordinator tries to minimize the consumption from the electricity grid. Finally, the Coordinator communicates with the Actuators, which send the orders to each appliance (Execution layer).

As an example, a simulation experiment is shown in

which the user wants to activate three appliances (washing machine, dishwasher and dryer) with some specific programs and within a defined interval (from 10 h., and finishing the washing machine, dishwasher and dryer before 17 h., 20 h. and 24 h. respectively). The main objective is to make the best use of PV electricity and batteries storage, reducing imports from the public grid. The batteries are supposed to be empty at the beginning of the day, to show a high level of interaction between the different electricity sources.

As aforementioned, the Control system must have information about the consumption of each appliance for the specific program to be used. Therefore, these consumptions have been experimentally measured and modelled according to their different operation modes (programmes).

Figure 8 shows the daily evolution of PV electricity together with the load consumption pattern for the best planning selected by the Coordinator. In Figure 9 a close view of the main consumption period is shown, the order of appliances used being: 1st-washing machine, 2nd-dishwasher, and 3rd-dryer. The loads demand and PV electricity are shown again (blue coloured P_{pv} and red coloured P_l, respectively), together with the breakdown of power sources supplying the loads: PV electricity ($P_{pv,l}$, green colour), electricity taken from the batteries ($P_{bat,l}$, pink colour) and grid electricity ($P_{grid,l}$, black colour).
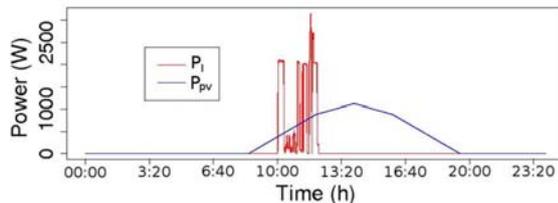
Figure 8: PV generation and optimal loads pattern
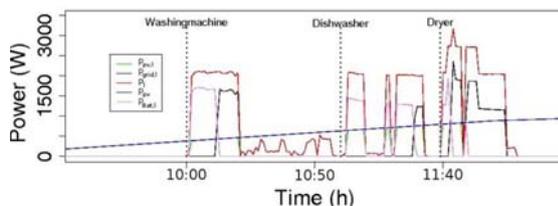
Figure 9: Close view of the consumption period

Note that when there is enough electricity generated by the PV strings the loads' consumption is supplied entirely by it. However, when the loads' consumption is higher, electricity is extracted from the batteries. This is what happens, for example, after ignition of the washing machine (10 h.): between 10 and 10:10 h., when the demand is $P_l \sim 2$ kW and $P_{pv,} = P_{pv,l} \sim 0.5$ kW, $P_{bat,l} \sim 1.5$ kW is supplied by the batteries. After the electricity available within the batteries has been used (at 10:10 h., remember that the batteries were empty at the beginning of the day, so that the electricity stored at 10 h. was the one produced by the PV strings up to that moment), the system starts importing electricity from the grid to complement PV generation ($P_{grid,l} \sim 1.5$ kW). A similar situation also happens after ignition of the dishwasher and dryer, as shown in the figure.

Figure 10 shows the 3 planning created by each of the appliances in terms of energy balance, where the time

start of each one is shown. As it can be seen, Figure 10(a) is the one with the maximum use of PV electricity to supply the loads at the end of the period ($E_{pv,l}$, green colour) and minimum use of grid electricity ($E_{grid,l}$, red colour). This is the reason why it was selected by the Coordinator as optimal consumption pattern, shown in Figures 8 and 9.
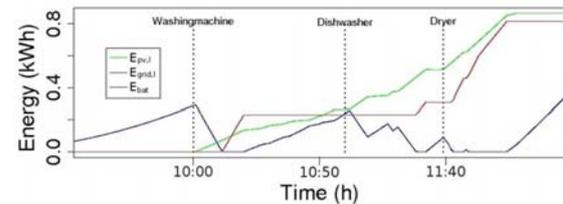
(a) Washing machine planning
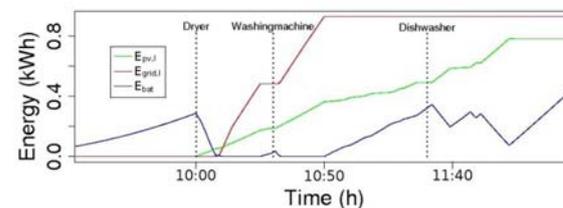
(b) Dryer planning
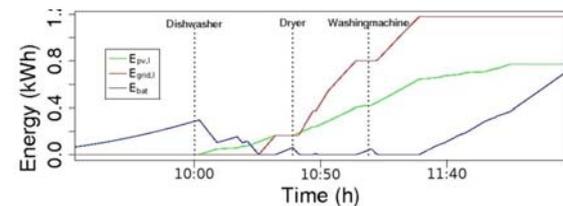
(c) Dishwasher planning

Figure 10: Energy planning of the 3 appliances

6   CONCLUSIONS AND FUTURE WORK

An active electricity management system for the residential sector has been presented, which combines a new generation hybrid PV system with strategies of Demand Side Management performed by an intelligent Control system. In this way, the system is able to displace the consumer's load curve in response to local and external conditions, thus optimising the PV use and enhancing the PV value for the user.

The next steps of the "GEDELOS-PV" project will be to integrate within the system a predictions block of the expected PV generation (based on the work presented in [9]) and to validate the complete GEDELOS-PV system with a new set of experiments where different economic frameworks (different tariffs for PV electricity and electricity consumed) will be considered. Also, in order to assess the benefits of multiple operation of this type of system, cooperation strategies will be analysed, both amongst users and towards the grid.

7   ACKNOWLEDMENTS

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