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Demand Response and Energy Storage for Zero Energy Residential Buildings

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Abstract

The EU climate and energy targets and the decreasing costs have been leading to a growing utilization of solar photovoltaic generation in residential buildings. However, even in buildings with the same level of yearly generation and consumption the mismatch between the demand and the photovoltaic generation profiles leads to high power flows between the household and the grid, which is an inefficient mode of operation. Therefore, new solutions are needed to increase the matching between the demand and the available generation.

This paper presents a novel energy monitoring and control system which integrates a PV generation and storage system designed for the residential context. Such system increases the matching between the local generation and consumption using lithium-ion batteries as storage device and the rescheduling of washing and drying appliances and the control of thermal loads (e.g., refrigerators or HVAC) as demand response resources. The system is controlled with the objective to minimize the power flows between the household and the grid, as well as to reduce the costs of operation.

1. Introduction

The household of the future should progressively become a Nearly Zero Energy Building (nZEB), and, to achieve it, the use of self-generation is fundamental. In residential buildings, photovoltaic (PV) generation is the most adopted technology and presents a fast-growing penetration [1]. However, unlike conventional capacity, PV generation cannot be reliably dispatched and exhibits significant temporal variability. Additionally, in residential buildings, the PV generation and electricity consumption do not have the same variation profile and such mismatch brings the need to export to the grid a significant part of the locally generated energy, even though the same amount of energy is later imported back for local consumption. These aspects are a source of inefficiency and create problems on the electrical grid management and can be even a source of economic losses to the end-user (in situations where the price paid by the consumed energy is higher than the price received by the energy injected into the grid).

At the same time, the energy consumption in European Union (EU) households has been steadily growing during the last few years due to the widespread utilization of new types of loads and the requirement of higher levels of comfort and services [2]. However, if properly controlled, several residential appliances can be used as a Demand Response (DR) resource, therefore contributing to minimize the mismatch between the generation and consumption [3]. Washing and drying appliances can be rescheduled to periods of lower energy consumption (thus flattening the demand curve) or of higher energy generation coming from renewable sources (thus matching consumption with renewable generation). The thermal loads (cold appliances, water heating or space conditioning) can be interrupted during shorts periods of time, without major reductions of service quality, to avoid the most unbalanced situations between generation and consumption, compensating the effects of the variability and randomness of the renewable resources availability.

Meanwhile, energy storage has emerged as a very important solution for this new paradigm, since it can store the surplus of generation to be used later in the periods with high consumption and small or null generation [4]. The cost of the storage technologies is decreasing, and soon it is expected to become economically suitable for small applications.

At the same time, new real-time monitoring and control systems have been developed to the residential sector to achieve energy and costs savings. Such systems could also be used to ensure optimization objectives and to improve the grid reliability, using electrical appliances as a demand response (DR) resource and managing the energy storage resources. This paper presents a novel energy monitoring and control system, based on the architecture developed by the ENERsip project [5] (other projects such as the Power Matching City project also use a similar architecture [6]), which integrates a PV generation and storage system designed for the residential context. Such system ensures the matching between the local generation and consumption using lithium-ion batteries as storage device and the rescheduling of washing and drying appliances and the control of thermal loads (e.g., refrigerators or space conditioning) as demand response resources.

The remainder of the paper is structured as follows. Section 2 presents the sizing of the PV and storage systems with the aim to convert a residential building in Portugal into a nZEB. Then, Section III, presents the design of the generation and storage system, as well as the information and communications technology (ICT) architecture that enables its monitoring and control. Section 4 presents the energy services offered by the system and its role on the optimization tasks. Section 5 presents the assessment of the impact of the use of DR and energy storage from the technical and economic point of views. Finally, Section 6 summarizes the paper, emphasizing its main conclusions.

2. Sizing of the System

In order to achieve a Zero Energy Building, the architecture and thermal optimizations are not enough, but also improvements in the electrical systems are needed. Furthermore, it is important to know how much renewable energy and storage capacity are needed and how they should be managed to optimize the expected benefits for the grid and for the customer. Therefore, a PV and energy storage system was sized to the average Portuguese household.

The survey on energy consumption in the residential sector, developed by the National Institute of Statistics and the Direction-General for Energy and Geology [7], assessed the average consumption of electricity per household in Portugal as 3673 kWh/year, which is about 10 kWh/day. Such survey also assessed the ownership rates of each type of appliance in the Portuguese households. Then, the electricity consumption breakdown in EU households was used as reference [2] and adapted to the Portuguese reality using the ownership rates of each appliance. Figure 1 presents the load profile considered for an average household in Portugal.
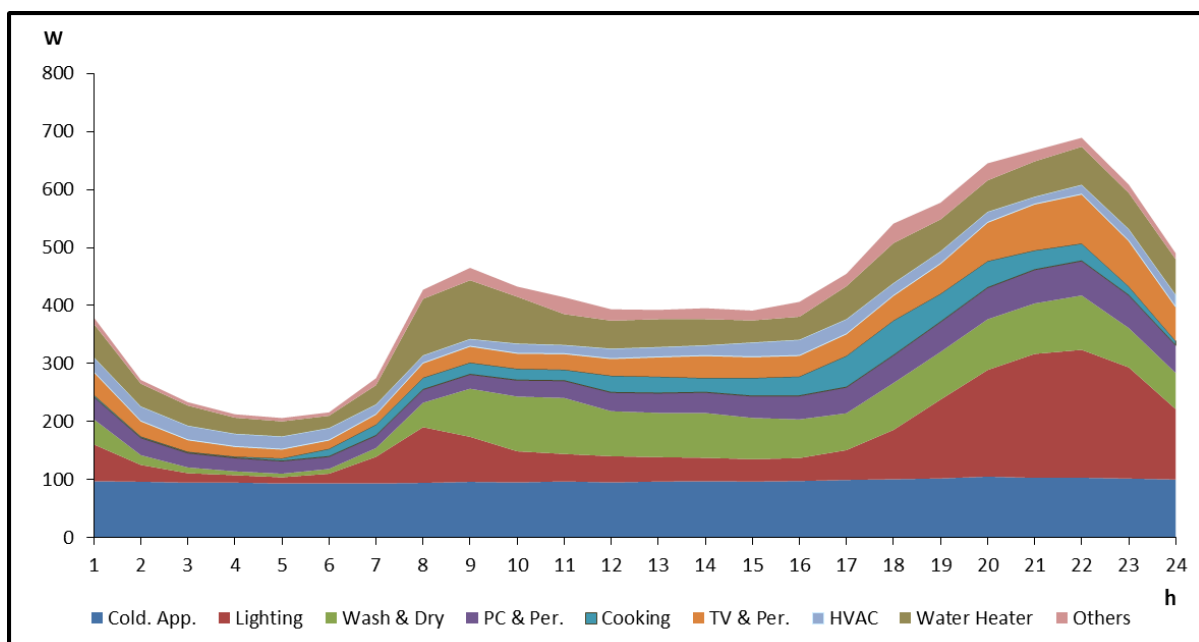

Figure 1: Load profile of an average household in Portugal

Considering the average solar radiation conditions in Portugal, the generation system was sized in order to ensure an average generation level equivalent to the average energy consumption (3673 kWh/year). To ensure such conditions a PV system with a total of 2.4 kWp is needed. Therefore, it was considered the use of 10 PV panels with 240 Wp, connected in 2 strings of 5 panels in series.

It was preciously assessed that to ensure a good level of generation and consumption matching, an effective energy storage capacity of 60% of the average daily consumption is needed [8]. Therefore, to the average Portuguese household the needed effective capacity of the energy storage system is about 6 kWh. Additionally, to avoid a quick degradation of the batteries, the State of Charge (SoC) should not be lower than 30% (increasing the needed capacity to 8.57 kWh). Considering the use of lithium-ion batteries with an efficiency of 92%, the needed minimum storage capacity is 9.32 kWh. However, the default value available in the market is 10.2 kWh. Therefore, to achieve a nZEB level in an average residential building, the use of a PV system with 2.4 kWp and an energy storage system of lithium-ion batteries with 10.2 kWh was considered.

3. System Architecture

3.1 Generation and Storage System

Figure 2 presents the proposed configuration to the grid connected PV generation and battery storage system. The 2.4 kWp PV array is connected to the DC bus by a boost converter with the duty cycle controlled to ensure the Maximum Power Point Tracking (MPPT) using an Incremental Conductance algorithm [9]. The MPPT algorithm ensures that the PV panel provides always the maximum power, regardless the load connected to its terminals, playing an important role for this kind of solar energy utilization, since it increases the PV panel efficiency. Its implementation is done through a DC-DC converter, and the operating principle consists in regulating the converter duty cycle in order to regulate the voltage (or current) output, extracting, thereby, the maximum power from the panel.

The 10.2 kWh (200 Ah, 51.2 V) lithium-ion battery is connected to the DC bus by a bidirectional DC-DC converter. The battery charging and discharging processes is ensured by the bidirectional DC-DC converter which operates in buck mode, during the charging process, and in boost mode, during the discharging process. The duty cycle of the bidirectional DC-DC converter is controlled according to the amplitude of the needed charging or discharging current. The DC bus is connected to the grid and to the loads by a 5 kVA, 100 kHz inverter, controlled by the hysteresis current [10].
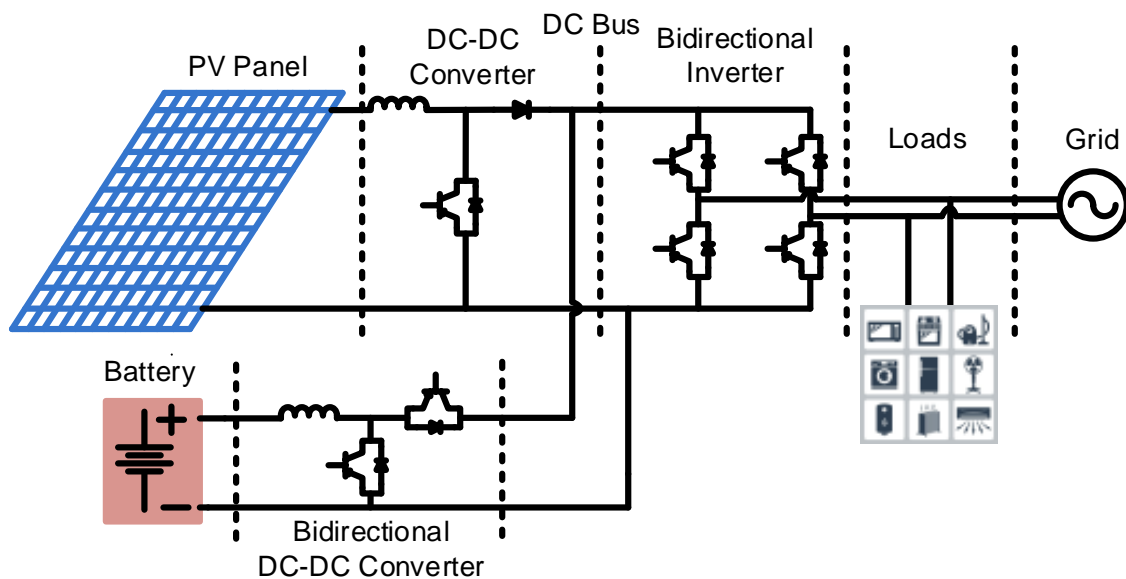

Figure 2: PV generation and storage system

3.2 Monitoring and Control Communications System

Monitoring and control communications infrastructures are crucial in order to achieve on-site consumption and generation matching in practice, since they allow collecting in almost real-time the consumption and generation data required by the optimization algorithms and delivering the appropriate commands at due time. As it has already been mentioned in section 1, the monitoring and control system for the consumption and generation infrastructures of nZEB proposed in this paper takes the communications architecture developed in the EU FP7 project ENERsip as baseline [5]. However, it has been updated to adapt it to the new specific scenario (including energy storage) and market trends.

Figure 3 shows an overview of the proposed monitoring and control communications system. As it can be seen, the sensors and actuators for the consumption and generation infrastructures communicate with the so-called Home Energy Manager (HEM). The protocol stack used for such communications is left open to implementation, being assumed that the communications requirements of the proposed optimization algorithms (e.g., in terms of latency) are met.
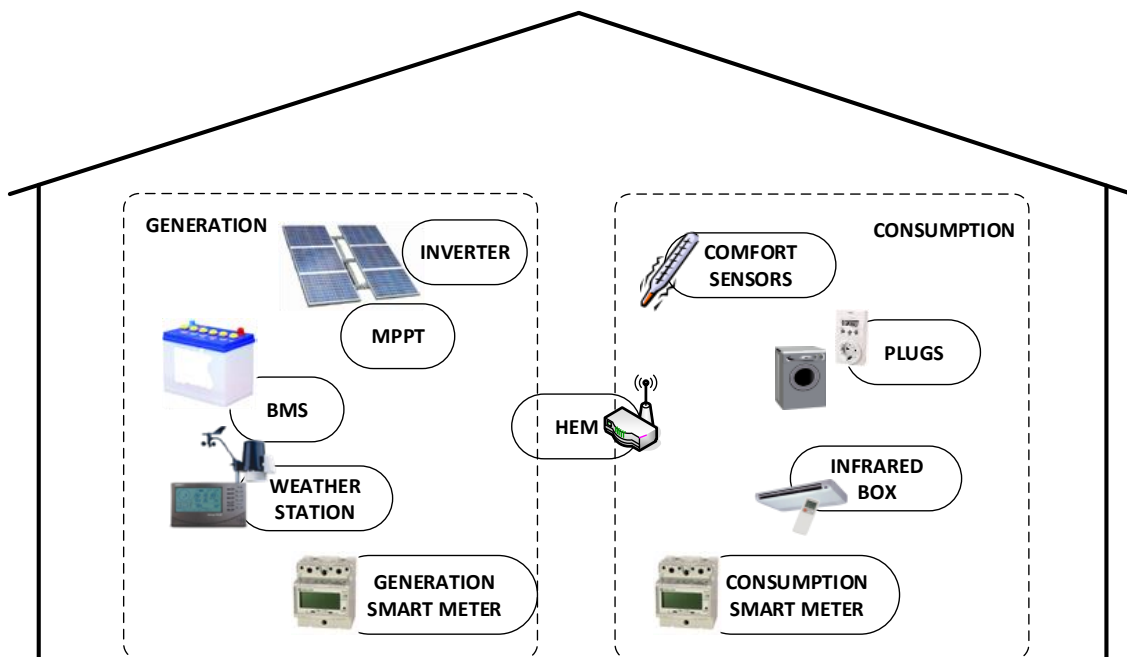

Figure 3: System architecture

The sensors and actuators considered for the consumption infrastructure are: Smart Plugs, Infrared Box, and Comfort Sensors [11]. The Smart Plugs are placed between the plugs of the appliances and the wall sockets. The Smart Plugs measure the consumption of appliances such as washing machines or driers and send it to the HEM, and also act on the power supply of such appliances by cutting it OFF or ON. The Infrared Box enables managing IR-controlled appliances, such air conditioning or multimedia devices such as TV or DVD, remotely. Both the Smart Plugs and the Infrared Box allow the integration of legacy appliances into the in-house/in-building monitoring and control system right away, thus enabling putting the proposed optimizations into practice even before the "smart appliances" come to the market. Finally, the Comfort Sensors measure different environmental variables, such as temperature, relative humidity or CO_2 concentration, which need to be taken into account by the optimization algorithms to avoid compromising the users' comfort levels.

As it has already been explained, the equipment considered in this paper in the on-site generation infrastructure involves photovoltaic panels and lithium-ion batteries. The sensors and actuators considered for this infrastructure are: Inverter, MPPT, battery management system (BMS), and Weather Station. The Inverter is associated to the PV panels and is responsible for DC-AC conversion. The MPPT module is also associated to the PV panels and works both as a sensor (measuring the voltage and current at the PV panel terminals and sending these data to the HEM)

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and as an actuator (controlling the duty cycle based on the commands received from the HEM, resulting from running the incremental conductance algorithm). The BMS module is associated to the energy storage equipment and manages the battery charging and discharging process by controlling the buck/boost converter. Hence, the BMS module also works as a sensor (measuring the voltage and current at the battery terminals and sending these data to the HEM) and as an actuator (handling the signal to charge or discharge received from the HEM and the current of discharge). Finally, the Weather Station gather several sensors that measure variables related to weather conditions and send these data to the HEM to enable accurate energy generation forecast. As a matter of fact, deploying a Weather Station is not actually mandatory in order to get such data, since the HEM could download them from a weather forecast web service.

In addition, a Consumption Smart Meter and a Generation Smart Meter are required to monitor and record the consumption and generation of the house/building. Such Smart Meters communicate with the Distribution System Operator (DSO), but also with the HEM (as it is currently being imposed by regulation), that uses this information to double check the effectiveness of its management commands. The HEM works both as a communications gateway and as an energy manager. Since in principle the consumption-generation matching is performed locally, the optimization algorithms run in the HEM. If this were not possible in practice (e.g., due to hardware constraints), the optimization algorithms could be run in a cloud-computing-based backend. The HEM may also communicate with the DSO and incorporate signals coming from them to its decision-making logic.

4. Energy Services and Optimization

The presented architecture enables the implementation of several energy services, such as: monitoring, remote control, demand response, local optimization and grid management.

The monitoring service provides information in real time about the energy consumption of the whole building and individual appliances and associated costs, the generation level and generation forecast, stored energy, energy injected into the grid and associated price. Such service ensures, not only an increase of the user awareness about the energy consumption (leading to energy savings), but also the identification of the resources available for optimization (loads available to be controlled, generation level and storage level).

The remote control service enables the remote control of individual appliances. The end-users can create an initial configuration of the network of energy consuming devices, turn a selected device ON or OFF, or change its properties (e.g., the air conditioning operating temperature). The parameterization of the network is a simple operation that can be done by an average household consumer, since they just have to use an intuitive interface to select the appliances, assign an operation period or turn it ON or OFF. This service is not just important to provide to the users the capability to turn OFF the appliances which are unnecessarily turned ON to reduce the energy consumption, but also to perform similar actions automatically through DR events. With such service, it is possible to turn OFF remotely any appliances and therefore the appliances used in DR can be easily controlled by the system, without the need of any manual operation.

With the demand response service, the end-user is able to specify individual devices or groups of devices to be included in the DR program (the home owners are notified about of pricing and load control events in the previously day), and consequently, those devices are directly controlled by the system (the user can also manually override it). This ensures the minimization of costs to the end-users (by shifting loads to periods with lower tariffs), but also the adequate management of DR requests received from the utility and management of loads to local optimization.

The local optimization service ensures the matching between the local generation and energy consumption. To ensure it, the service uses the demand response service by rescheduling appliances to the periods with high energy generation or by curtailing thermal loads in situations of a quick decrease of generation. Additionally, it ensures the optimization of the energy storage ensuring that a minimum SoC of 30% is always guaranteed and considering the available capacity in the battery it assess the energy to the stored, sent to the grid or consumed from the grid, in each time slot, considering the priorities presented in Table 1.

The grid management service provides to the Distribution System Operator near real-time information about generation and consumption of electricity, as well as stored energy in a given location. Such information will be very important for the DSO to the planning and dispatching of the generation resources. However, the most important impact of this service is to ensure the required conditions to operate DR programs, namely providing data about the available loads in each neighbourhood, providing communication channels to send real-time tariffs and ensuring the ability to remotely control the appliances according with the user preferences. Using the same principle, the service could also ensure the needed conditions to the use of the stored energy to provide ancillary services to the DSO.

Table 1: Priorities of the energy storage optimization

Battery	Generation > Demand	Generation < Demand
SoC = 30%	1. Needed generation to loads 2. Remainder generation to storage	1. Available generation to loads 2. Remainder energy need received from grid
30% < SoC < 100%		1. Available generation to loads
SoC = 100%	1. Needed generation to loads 2. Remainder generation to grid	2. Available stored energy to loads 3. Remainder energy need received from grid

5. Impact of the Optimization

The global system, its individual components (PV panels, batteries, etc.) and its management and control system were modelled in MATLAB/Simulink (Figure 4). Such model was then used to simulate the impact of the control under different conditions of operation.
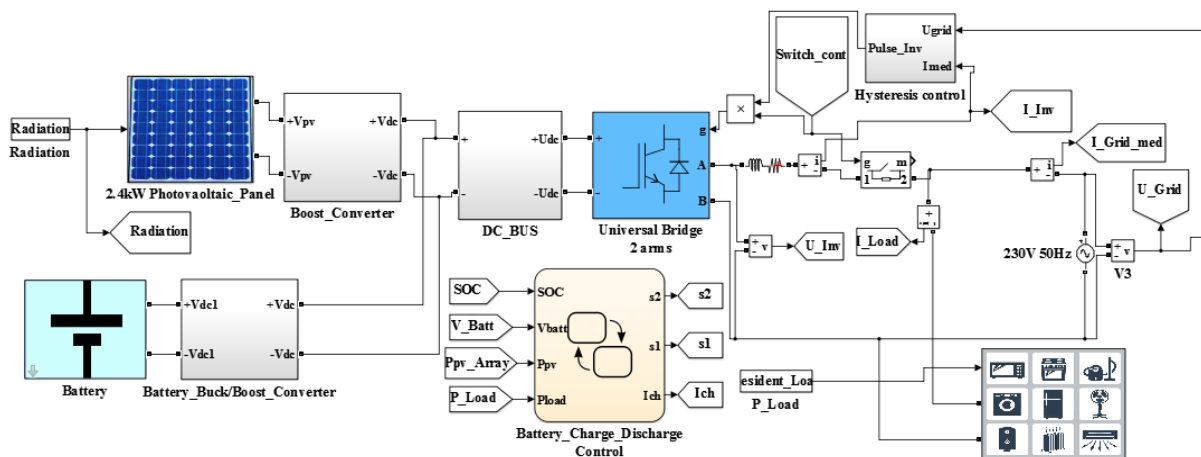

Figure 4: MATLAB/Simulink model of the system control

5.1 Baseline

The assessment was done to the entire year, but only data from three months is presented to represent different extreme conditions: August (higher generation), October (almost the same level of generation and consumption) and December (higher consumption). Figure 5 presents the generation profile, the demand profile and the exchange of energy with the grid (difference between the generation and consumption levels). In a household without control of loads and without energy storage there is a constant power flow between the grid and the household, sending most of the generation to the grid and receiving from the grid all the energy needed during the night. As can be seen in Table 2, in such conditions between 53.4% and 71.5% of the generated energy is injected into the grid (H2G) and, simultaneously, between 56.2% and 74.1% of the consumed energy must be requested to the grid (G2H).
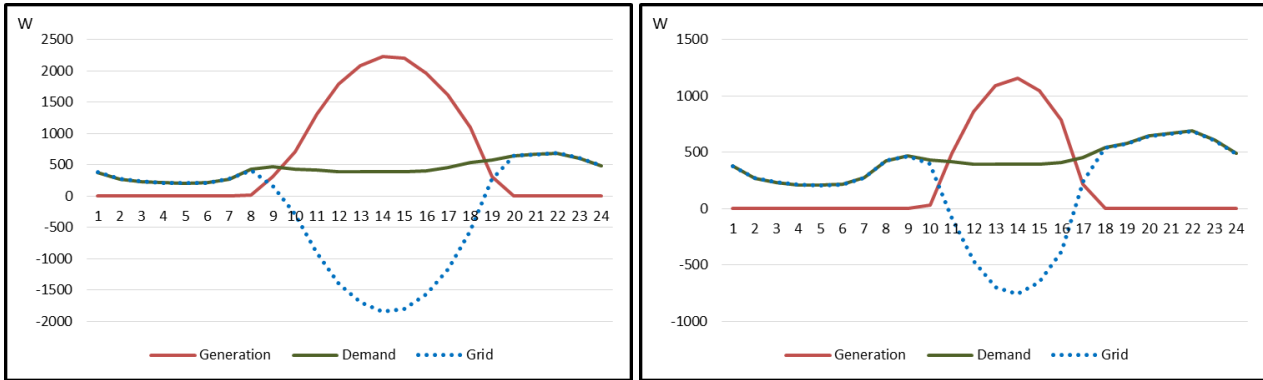
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Figure 5: Generation, demand and exchange with the grid in August (left) and December (right)

Table 2: Daily energy exchange between the household and the grid

	August	October	December
H2G (Wh)	-11177.5	-6618.0	-3028.1
G2H (Wh)	5728.7	6729.0	7546.6
H2G (% Gen.)	-71.5%	-65.7%	-53.4%
G2H (% Dem.)	56.2%	66.0%	74.1%

Such high power flows do not have just a technical impact but also an important economic impact. With the new Portuguese regulation to self-consumption of locally generated electricity, the energy injected into grid is paid only with a price of 90% of the monthly average price of the Portuguese spot electricity market. During 2014 the average price of the Portuguese spot electricity market was 0.0427 €/kWh and therefore it was considered a price paid by the electricity injected into the grid of 0.0384 €/kWh. Since the energy received from the grid has a much higher cost (0.2206 €/kWh during on-peak periods and 0.1174 €/kWh during off-peak periods) any energy sent to the grid will lead to economic losses. As can be seen in Table 3, in such conditions there is an average daily cost between 0.49 and 1.21 €, since the costs of the energy consumption are much higher than the profit obtained with the energy injected into the grid (considering the same average generation and consumption).

Table 3: Energy costs

	August	October	December
Generation (€)	-0.43	-0.25	-0.12
Demand (€)	0.92	1.14	1.32
Total (€)	0.49	0.89	1.21

5.2 Demand Response

Figure 6 (left) presents the load profile from Figure 1, but aggregating the consumption by the three main types of appliances: non-controllable, interruptible and reschedule appliances. The interruptible appliances can be used for generation and consumption matching objectives by temporarily reducing or cutting the consumption of such appliances to compensate reductions in the generation. This is very important to compensate the intermittence of large scale wind power and therefore can be used to supply services to the system operator. Likewise, it can be used to the optimization between the local generation and consumption, but since it is just used in rare occasions it does not have a relevant impact on the global power flows between the household and the grid and on the associated costs. The group of appliances with the most relevant impact are the reschedule appliances, since by rescheduling such appliances to operate only during the hours with high PV generation it is possible to reduce the energy sent to the grid during the hours with generation and reduce the energy received from the grid in the hours without generation. Figure 6 (right) presents the load diagram with the considered reschedule of average consumption.
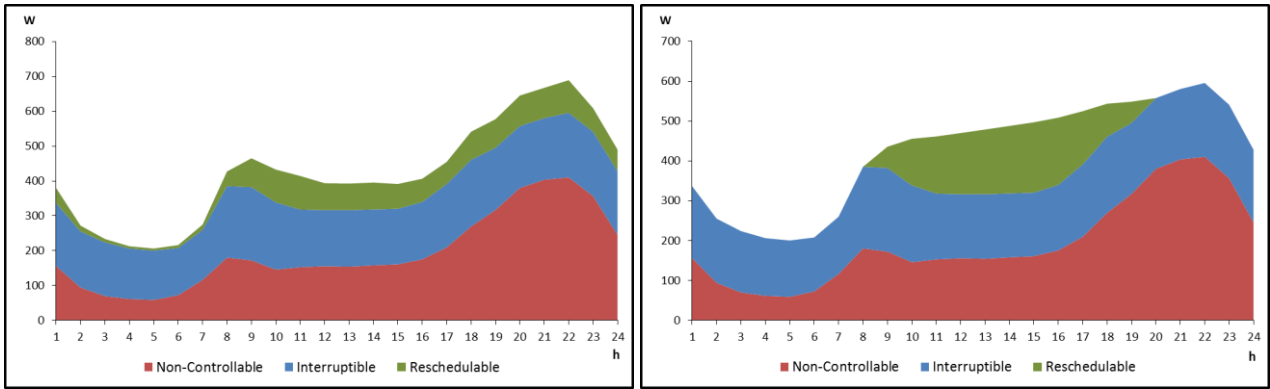
Figure 6: Load profile without (left) and with reschedule (right) of loads

Figure 7 presents the impact of the rescheduling on the energy exchange between the household and the grid. The figure presents the generation profile, the demand profile with and without rescheduling and the exchange of energy with the grid, in the scenarios with and without rescheduling. As can be seen in Table 4, such strategy leads to a decrease between 5.4% and 16.8% on the energy sent into the grid and, simultaneously, a decrease between 6.7% and 10.5% on the energy consumed from the grid
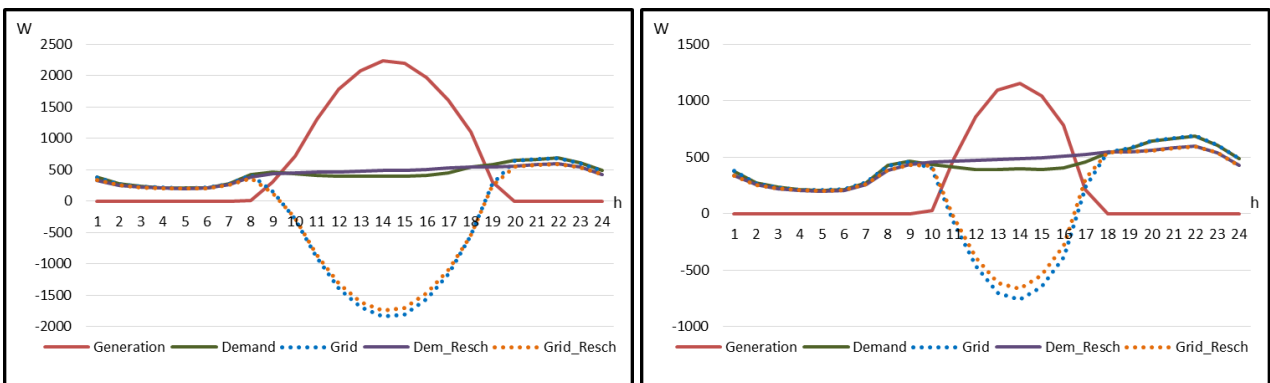

Figure 7: Generation, demand and exchange with the grid in August (left) and December (right) with and without reschedule of appliances

Table 4: Daily energy exchange between the household and the grid considering reschedule of appliances

	August	October	December
H2G (Wh)	-10573.5	-6016.3	-2519.0
G2H (Wh)	5124.7	6127.3	7037.6
H2G (% Gen.)	-67.6%	-59.7%	-44.4%
G2H (% Dem.)	50.3%	60.1%	69.1%
ΔH2G (%)	5.4%	9.1%	16.8%
ΔG2H (%)	10.5%	8.9%	6.7%

Such reduction on the energy exchanged between the household and the grid also have as impact a reduction between 5.3% and 16.5% on the daily costs, as can be seen in Table 5.

Table 5: Energy costs considering reschedule of appliances

	August	October	December
Generation (€)	-0.41	-0.23	-0.10
Demand (€)	0.82	1.04	1.24
Total (€)	0.41	0.81	1.14
ΔTotal	-16.5%	-9.1%	-5.3%

5.3 Energy Storage

By including the impact of the designed storage system it is possible to absorb the excess of energy generated during the hours with sun to use it during the night, minimizing the exchange of energy between the household and the grid. However, since there are high variations during the year in the generation, due to the limit of the storage capacity, it is not possible to entirely eliminate the exchange of energy. Figure 8 presents the variation of the SoC of the battery during an average day in August and December. As it can be seen, during August the maximum SoC (100%) is achieved (leading to the injection of energy into the grid) and in December the minimum SoC (30%) is achieved (leading to consumption of energy from the grid).
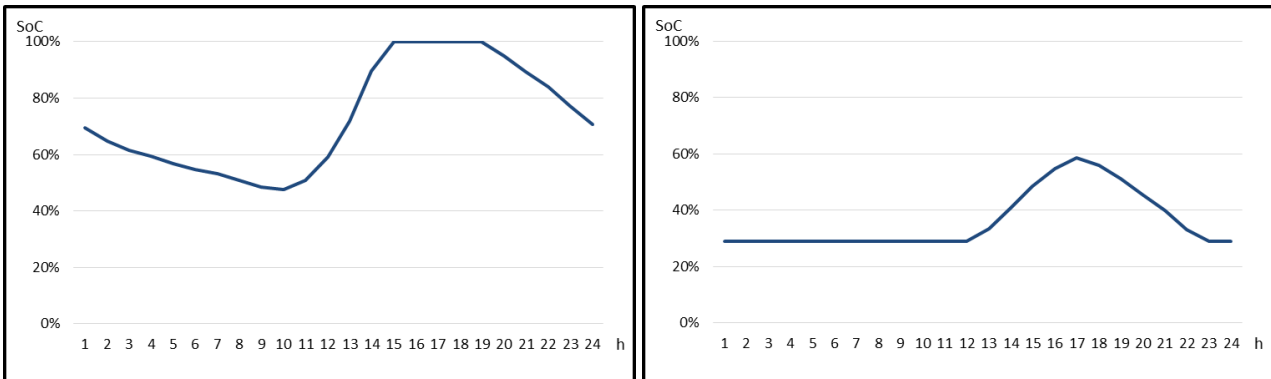

Figure 8: Battery State of Charge in August (left) and December (right)

Figure 9 presents the impact of the energy storage, showing the generation profile, the demand profile and the exchange of energy with the grid, in the scenarios with and without energy storage. With the optimization ensured by the storage system, even in these extreme situations of high and low generation, the exchange of energy between the household and the gird is low, since there is just energy sent to the grid when the SoC is 100% and energy consumed from the grid when the SoC is 30%.
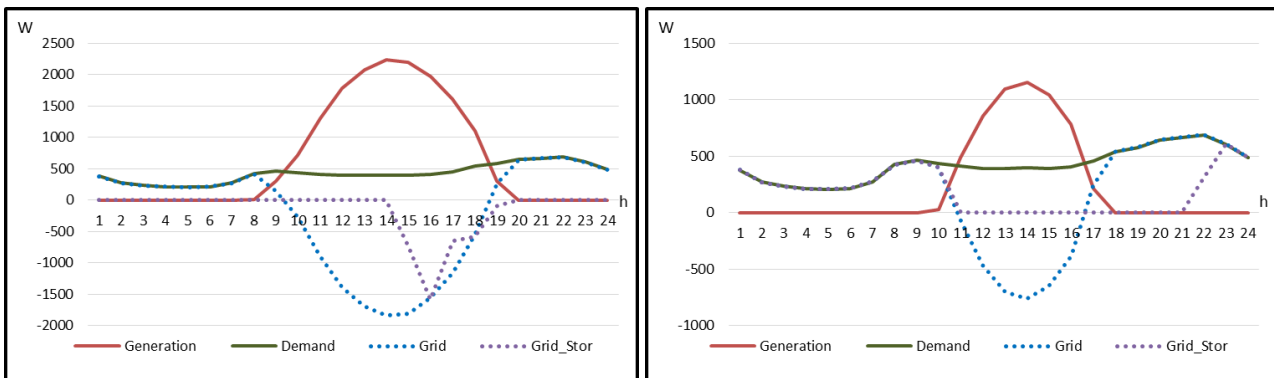

Figure 9: Generation, demand and exchange with the grid in August (left) and December (right) with and without energy storage

As can be seen in Table 6, such strategy leads to a decrease between 67.5% and 100% on the energy sent into the grid and, simultaneously, a decrease between 40.4% and 100% on the energy consumed from the grid.

Table 6: Daily energy exchange between the household and the grid considering energy storage

	August	October	December
H2G (Wh)	-3636.6	0	0
G2H (Wh)	0	123.03	4495.7
H2G (% Gen.)	-23.3%	0%	0%
G2H (% Dem.)	0%	1.2%	44.1%
ΔH2G (%)	67.5%	100%	100%
ΔG2H (%)	100%	98.2%	40.4%

Such reduction on the energy exchanged between the household and the grid also have as impact a major reduction on the average daily costs, which decreases between 46.2% and 131.8%, as can be seen in Table 7. It is important to note that the daily average cost achieved during the average month (October), and therefore the average yearly cost, is almost 0 €. This is ensured due to the reduction of the energy injected into the grid that is paid with a low price and, simultaneously, by avoiding the consumption of energy during periods of high cost.

Table 7: Energy costs considering energy storage

	August	October	December
Generation (€)	-0.14	0.00	0.00
Demand (€)	-0.02	0.01	0.65
Total (€)	-0.16	0.01	0.65
ΔTotal	-131.8%	-98.4%	-46.2%

6 Conclusions

This paper presents an energy monitoring and control system which integrates a PV generation and storage system designed to be used in residential buildings in the context of Zero-Energy Buildings (considering the same level of yearly generation and consumption). The sizing of the energy generation and storage system (using photovoltaic panels and lithium-ion batteries) was done to convert a residential building in Portugal in a nZEB. Then, the system architecture for the generation and storage system, as well as for the monitoring and control system was designed. The energy services needed for the implementation of DR actions and for the management of energy storage were defined and the optimization rules were set with the objective to simultaneously minimize the power flows between the household and the grid and the costs of operation.

The system was modelled in MATLAB/Simulink and its operation was validated showing the reliability of the designed system and its control. The model was then used to simulate the impact of the system under different conditions of solar radiation and demand. The results show that with the implementation of DR actions it is possible to achieve an average reduction of about 9% on power flows and costs. Adding the impact of the energy storage management, the reduction of power flows and costs increase to about 98%, therefore showing the key role that DR and energy storage can have in buildings with local generation.

Despite the cost savings that can already be ensured with the use of energy storage and DR in the Portuguese households with PV generation, such savings are not enough to ensure the cost-effectiveness of the system. However, due to the fast reduction of costs of energy storage devices that is projected to the next years, such systems should be cost-effective before 2020. In a future work, a prototype of the proposed architecture is going to be tested in a real household.

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