Evaluation and Integration of Demand Response and Photovoltaic Generation in Institutional Buildings

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***Abstract*—Buildings are an important segment from the point of view of the overall consumption and the flexibility or change in their demand through Demand Response, Energy Efficiency and Renewable Sources. The integration of renewables represents an opportunity for buildings because main end-uses (for example heat, cool, and ventilation) follow, at some extend, the potential of solar resource. The problem is that renewable resources are evaluated through simulators from average conditions (irradiation, external temperature) but in practice, and in the short term, the generation resource exhibits an important volatility and, in some cases, the integration of renewables can produce not only benefits but risks for the customer from an economic aspect. The aim of this paper is the evaluation of these risks, and to state how Demand Response policies and, of course, Renewable Energy Sources (RES) models, can help to reduce or mitigate these risks and volatility. A real university building is presented to exemplify the methodology.**

Keywords—Demand Response, Forecasting, Renewable sources, Energy Markets, Energy Management in Buildings

I. INTRODUCTION

Buildings are responsible for 40% of energy consumption and 36% of CO_2 emissions in the EU. According to Energy Performance of Buildings Directive (EPBD), two mechanisms will be decisive for the development of the building sector [1]: First, the energy required should be covered to a very significant extent by energy from renewable sources, including energy produced "on-site", usually from PV. This self-generation balances demand of heat pumps or other Heat, Ventilation and Air Conditioning (HVAC) systems. Second, the retrofit of elements that form part of the building envelope can reduce thermal losses through walls and windows, and air infiltrations.

In the South of Spain, buildings and Distributed Energy Resources (DER) have some pros and cons. The problem of a lot of buildings (e.g. institutional ones) is the age of these buildings (20 to 40 years old) and the quality of building envelope before the publication of EU directives (EPDB, Energy Efficiency [1]). The main advantages are the availability of solar resource due to high radiation levels and the fact that HVAC reversible systems are economically attractive in the Mediterranean climate. Several HVAC manufacturers report a growing market scenario [2].

Limitations for renewable sources arise due to disparities in time or location, but especially if one technology is significantly favored or not by the markets or by specific regulations in each country. This last factor is a main concern for this paper because the availability to sell energy in markets, or the fixed and variable charges associated to self-generation (for example in Spain, see [3]), could condition the cost-effectiveness of DER projects in buildings.

Another factor to be taken into account is the interest for Demand Response (DR) policies worldwide [4], and a growing need to engage customers in energy policies, i.e. to achieve an active customer as one of the principal actors in markets [5]. In a scenario of integration of renewables, these DR resources can provide the necessary flexibility of power systems and could explain in the future the provision of some Ancillary Service.

There are some studies that discuss the implementation of DER and the effect of DR strategies on the energy consumption of small- and medium-size consumers with small-scale PV systems [6-8]. Reference [6] develops a practical experiment for studying the effects of Demand Response and Energy Storage Systems (ESS) on the consumption of a dwelling, with a 5.55 kWp PV system. A PV system and demand response strategies for lighting in an office building are applied in [7]. An economical and technical study is performed in order to evaluate the savings, obtaining reductions in energy consumption around 9%. In [8] a Demand Side Management (DSM) algorithm is proposed to overcome the variability of a

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small-scale PV system generation by modifying the load demand of air conditioning and ventilation system.

The idea of this paper is to present a mix of methodologies and its synergies that can help the development of DER, and specially Demand Response (DR) and Photovoltaic generation (PV) in medium-size customers while avoiding at some extend the uncertainty of RES and its consequences (for example the so called "Duck chart" in California [9]). In Section II, the approach to the problem, the characteristics of customers and their solar resource is presented, as well as the volatility of solar resource is analyzed. Then, in Section III, the effectiveness of the interaction between DR and PV is stated thorough simulations. Finally, in section IV, some conclusions are stated.

II. METHODOLOGY

The idea of the methodology being used in the paper is shown in Fig. 1. First, regulatory requirements (in Spain) are analyzed to establish a framework for DER. In a second stage, several models and tools are considered: for example, load disaggregation of overall demand trough Non-Intrusive Methodologies (NILM) or Energy Agencies reports [10] to evaluate main end-uses. Third, several simulators have been used: Physically-Based Load Models (PBLM) to consider the change in load pattern due to changes in weather (or changes due to DR policies [10]); models for RES (in this case, a well-known simulator SAM, NREL [11] has been used), and a numerical weather prediction (NWP) model to forecast the weather variables, specifically irradiation in the short time [12]. Fourth, some non-conventional storage possibilities [13] have been taking into account for simulation purposes (in our case indirect storage), and finally, energy prices and tariffs have been explored to evaluate different cost and benefit scenarios for the customer (size of PV system, the effects of time-of-use tariffs, changes in energy due to DR,…).

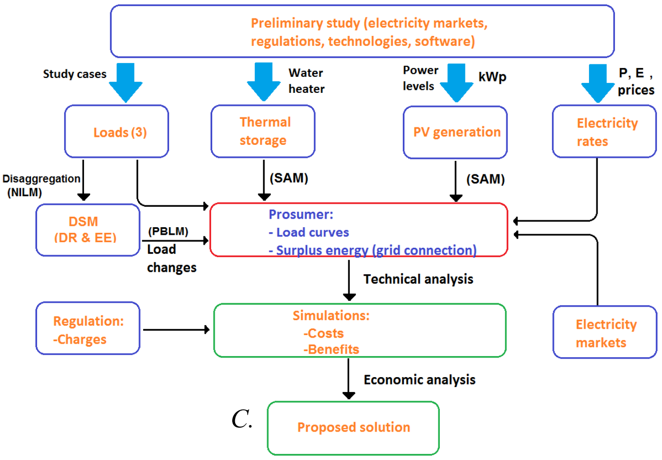

Fig. 1. Methodology

Regulatory requirements for DR and PV in Spain

The framework for DER in Spain in small/medium segments of demand is discouraging, and especially for DR (see [14]). But this scenario should change in the future UE energy market with a customer much more active [5] and consequently these segments should be able to evaluate their possibilities. With respect to self-consumption [3], this alternative appears as less interesting for customer that net balance or credits available for PV production in other countries [15]. In this scenario, PV generation should be planned to cover demand at high-price energy periods. Another problem is the near future in where imbalance can be a problem and the customer should apply for the provisioning of ancillary resources [16].

Customer characteristics and solar resource

The study is focussed on a University Building with a consumption of some hundreds of kW (peak around 400kW). The building includes classrooms, departments and administrative offices. HVAC explains about 40-50% of the overall demand, lighting 25% and Electronic appliances 15%. Fig. 2a shows a typical daily load curve for this building.

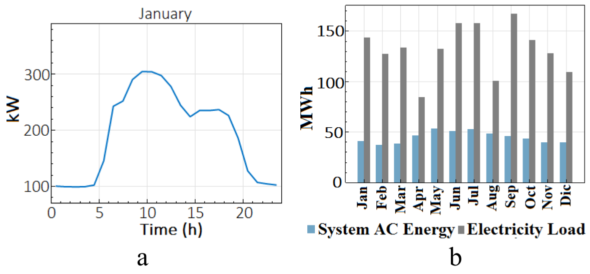

Fig. 2. a) Daily load (January): University building, b) Annual PV generation

The proposed tool (SAM [11]) analyses several rated power levels for PV arrays and their impact on the costs. Some results are presented in Fig. 2b. The analysis of this "business as usual" scenario is performed, through average-value for irradiation and other weather variables, taking into account that this kind of customer can benefit from ToU tariffs. The results show that 300kWp is the optimal level for the PV array, obtaining a payback period time around 10 years. This value may slightly oscillate (±0.5 years) due to the variability of the solar resource. Fig. 3 shows the behavior of PV generation and load during the different seasons for the average scenario.

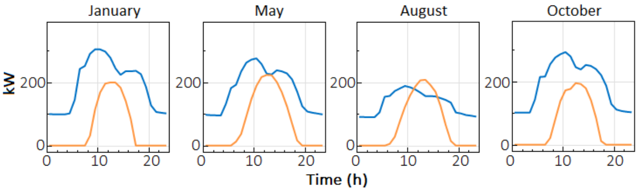

Fig. 3. Load (blue) and PV generation (orange) in the average scenario

Evaluation of the solar resource in the short-term

In order to evaluate de variability of solar PV with respect to conventional simulation scenarios, the solar resource in the winter season has been analyzed. The more changeable weather which increase the uncertainly in PV solar generation is the reason for choosing this time of the year. Average weather values have been obtained from PVGIS database for a

Typical Meteorological Year (TMY) [17]. Real values were obtained from a local weather station and forecasts were produced by means of the Weather Research and Forecasting (WRF) model [12]. The WRF model is an advanced NWP model designed to provide forecasts of weather variables in a mesoscale or regional scale, and it was used to forecast hourly values of irradiation, temperature and cloud coverage for the day-ahead (forecasting horizon of 24-48 hours) and for the location of the University Building. To obtain the PV production of the array, SAM has been used again. Fig. 4 shows a comparison between average values and real values of monthly PV production in winter for the 300 kWp PV system that has been chosen as benchmark.

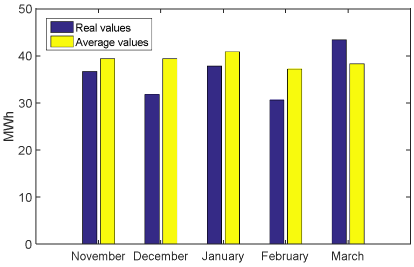

Fig. 4. Real (blue), and average (yellow) values for PV generation in winter

December and February are the months with the most variability, with a decrease in real generation of 7.6 and 6.6 MWh respectively compared to average values. However, in March, real predictions increase production in 5.1 MWh compared to average conditions. All this variations have to be evaluated in a shorter period of time to improve the performance of the PV-system and the loads' planning.

To analyze the short-term variations, a typical winter week has been studied using hourly data for solar PV production. Fig. 5 represent the 1 kW PV generation for one day obtained with average values (yellow), weather predictions made one day before (red) and real values (blue). It is observed that around 2 o'clock in the afternoon the real generation decreased considerably compared to the predictions. Other types of variations such as a punctual increase of generation will be shown later. The differences between predictions and real values cause some problems in the consumption's planning which will have to upload as soon as possible to the new conditions.

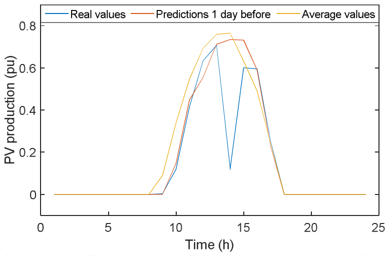

Fig. 5. Real (blue), predictions (red) and average (yellow) values for PV generation in one winter day

PBLM models for DR and some kinds of indirect storage

The availability for load response depends on load behavior and its characteristics (and its environment for the so called thermostatically controlled loads, TLC). Several approaches to evaluate DR can be found in the literature, some of them based on machine learning [18], but another interesting way to evaluate this response is through Physically Based Load Models (PBLM), methodology proposed first to solve cold load pickup in [19]. The main reason is that these models are "white" or "grey" models which allow to physically explain the dynamics of the load and consequently foresee its changes. In this paper a PBLM model for HVAC loads (heating and ventilation) previously proposed in [10] is used. Fig. 6 shows the electrical-thermal equivalent for this model (a broader explanation of parameter can be found in [10] and [20]).

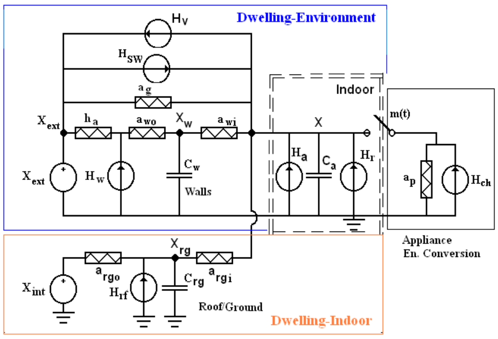

Fig. 6. Example of PBLM for a classroom of the building

Main features of the model are: it consider heat gains, for instance solar radiation (Hsw, Hw) or internal gains due to inhabitants (Hr) or appliances (Ha); the model takes into account heat storage from the specific heat of external walls (Cw), indoor mass (Ca) or roof/ground (Crg); and it considers the control mechanisms which drive DR policies (for instance thermostats m(t) in TCL. Moreover its state variables are temperatures: indoor (X), walls (Xw) and roof/ground (Xrg), a characteristic which allows an easy evaluation of energy stored in walls (in analogy with the energy stored by capacitors), i.e. the indirect capacity of storage in buildings (without additional capital investments in batteries) or the loss of service due to the application of DR.

III. RESULTS

Three different and real scenarios for short-term variations of PV production have been considered in this section (see Fig. 7). Also, DR policies, assisted through PBLM, have been applied to mitigate in some extend the problems caused by the changes in PV generation. The main objective of this section is to ensure that changes in generation do not modify the profile of energy demand and do not compel customer to trade additional resources into wholesale markets (energy and ancillary service markets). To achieve this goal, the HVAC load is selected for implementing control strategies because of their flexibility (achieved by changing the temperature of the thermostat).

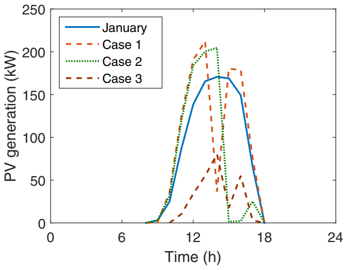

Fig. 7. Different scenarios for PV with respect to average values in January (blue curve)

Case 1. Moderate increases and decreases in PV

First case that have been studied consists on an increase of PV production between 10 and 12 am (27%) followed by a heavy decrease of PV generation (78%) for approximately 3 hours (with respect to average PV profile). Then, the PV generation exceeds the average again. To operate with these fluctuations between real and average production while balancing the net demand (i.e. minimizing the need for additional services in the markets [16]) it is necessary to modify the overall demand of the building (through DR or Demand Side Flexibility, DSF policies). Fig. 8 presents the target for the demand profile to balance the volatility in PV generation (predicted day-ahead, see section II.C). Blue curve shows the original overall load and purple dashed line represent the target for the overall consumption after applied DR mechanisms. For simplicity, only the main end-use, HVAC (its model was presented in section II.D) is managed by the customer (or more probably by its aggregator). Red curve represents HVAC demand without any DR action.

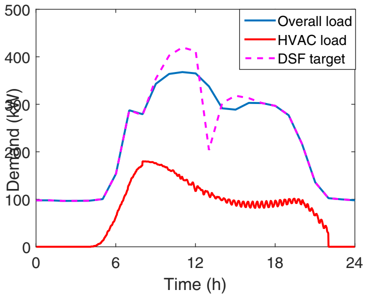

Fig. 8. Overall (blue) and HVAC (red) loads before DR strategies and DSF target (purple) from overall load.

In order to achieve the overall load profile target, DR mechanisms have been applied to HVAC end-use. Fig. 9 represents the changes in HVAC setpoint temperature evaluated through PBLM simulation. Blue dashed line show the internal temperature of one of the buildings (X_i) conditioned by HVAC loads without any DR action. Setpoint temperature is fixed in 18.7ºC since 9 o'clock in the morning. Red line represent the internal temperature (X_i) once DR mechanisms have been applied (the decrease of this temperature conditions the intensity of DR or DSF potential). To rise the demand, an increasing of the setpoint of thermostats (Δ=1.3ºC, from 18.7 to 20ºC) between 9h and 12h is applied. This increment produces a response and a greater energy consumption from HVAC load during this period to cover the rise in service level (X_i), which seeks to compensate the PV overproduction. It is interesting to note that this do not involves a loss of efficiency because this peak in demand "charges" the internal (hidden) reservoirs of energy storage (i.e. walls, roofs, see the slight increase of X_w in Fig. 9). This preheating of building, previously performed, allows to reduce the setpoint temperature to 18ºC at 12h30, and it contributes to maintain the internal temperature (and customer comfort) of the building when setpoint temperature is reduced. In this way, HVAC consumption decreases and fits the decrease of PV generation (of course at some extend). When PV generation overcome the average generation profile again, the setpoint temperature is modified to 19.5ºC (around 14h), increasing again the HVAC consumption for the purpose of using up the overproduction. Finally, when real and average PV production are equal again, setpoint temperature is returned to 18.7ºC. Notice that the increase of demand is not wasted but stored.

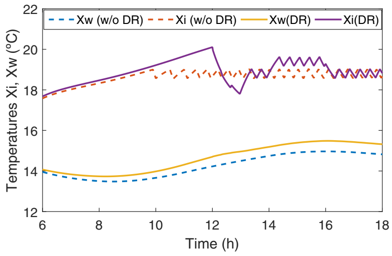

Fig. 9. Internal temperature (Xi) without DR (maroon) and with DR (violet); and walls' temperature (Xw) without (dashed blue) and with (yellow) DR.

Finally, Fig. 10 represent how the DSF target is reached by the changes in overall and HVAC load profiles after applying DR. Blue and violet lines show the original load profiles (without DR). Magenta dashed line represent the overall load target set by variations of PV production. Red line and green dashed line show the overall and HVAC consumption after DR actions are applied.

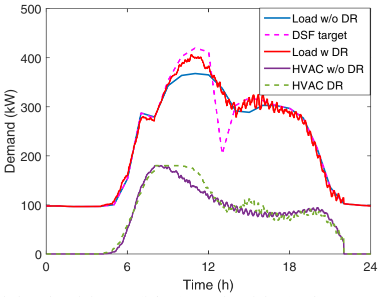

Fig. 10. Overall load without (blue) and with (red) DR, overall load target (dashed magenta) and HVAC load without (violet) and with (green) DR.

The increase of the HVAC consumption between 8:30h and 12h and between 14:30h and 17h produced an increase in overall profile (red line) which clearly allow to approach the target (magenta). Between 12h and 14:30h, a decrease of the HVAC consumption that approaches to the target is achieved but it is not enough so it is necessary to perform other DR actions (with other flexible loads such as Water Heating, WH, Lighting), or doing use of Ancillary services.

Cases 2&3. Heavy decreases in PV generation

Finally, two extreme cases have been considered. In both cases, the PV generation drops near cero with respect to average PV values during several hours (98 and 88%, see Fig. 7). This constraint seems to involve the application of heavy boundary conditions to the use of DR policies in HVAC loads (the loss of service in the temperature of the building, and a foreseeable rejection of customers to DR). The response to these concerns can be found in the hidden or internal storage X_w. Fig. 10a&b shows DSF targets for both cases, and again the HVAC load profile.

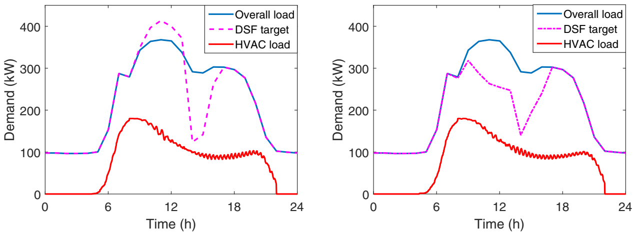

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Fig. 10. Overall (blue) and HVAC (red) loads before DR strategies and DSF target (purple) for two PV scenarios: a) Case 2; b) Case 3 (see Fig. 7)

In order to achieve the overall load profile DSF target, DR mechanisms have been applied to HVAC end-use again. Fig. 11a&b represent the necessary changes in HVAC thermostat setpoints tuned through several PBLM simulations.

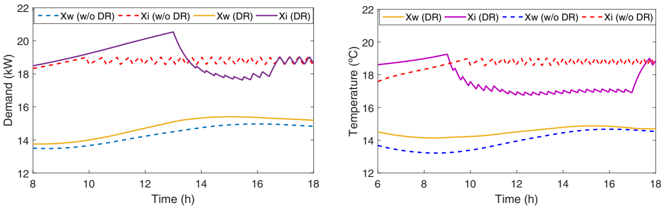

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Fig. 11. Internal temperature (Xi) without DR (red) and with DR (purple); and walls' temperature (Xw) without (dashed blue) and with (orange) DR: a) Case 2; b) Case 3.

Red dashed line show the internal temperature in a representative (mean) dwelling of the buildings (X_i) in steady state, i.e. without any DR action. In case 2, during DR, the setpoint temperature is fixed to 18.7ºC, starting around 8 in the morning. Case 3 forces the switching of HVAC loads from 4 at 6 a.m. to produce a rise in the internal temperature (X_i) as soon as possible, and consequently in (X_w) before any DR mechanism has to be applied.

In the case 2 the rise of demand is enforced by the increase of PV generation, whereas in the case 3, the preheating (two hours before from steady-state conditions) is due to the complete loss of PV supply (88-98%) and on the necessity to fill the "hidden/internal" reservoir (i.e. X_w) during off-peak ToU period (i.e. the lowest price of energy). In case 2, to produce the rise in the demand, an increasing of the setpoint of thermostats (Δ=1.8ºC, from 18.7 to 20.5ºC) between 9h and 13h is applied. This increment produces a response and a greater energy consumption from HVAC load during this period to balance PV generation (i.e. 27% of PV surplus).

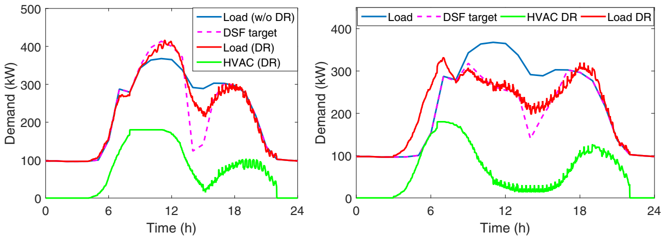

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Fig. 12. Overall load without (blue) and with (red) DR, overall load target (dashed magenta) and HVAC load with DR (green) for: a) Case 2; b) Case 3

Fig. 12a&b shows the results in the overall demand curve and allows the reader to verify the goodness of DR policies being applied to balance the volatility of PV generation.

It is important to note here that service of the customer is not heavy affected with DR. In the worst case (case 3) the internal temperature drops to a minimum of 16.8ºC for a control period of about 6hr, and this compliance and service is surveyed by the "white/grey-box" PBLM through the state of the load (dwelling) reservoir X_w.

Table I shows some values of how the volatility in PV generation can change the overall performance of the customer and how DR can reduce this damping for the three cases presented in the simulation examples. From these results, the volatility of peaks (kW) is not changed but this is due to the fact that demand peaks in the customer appear out of PV generation periods (early morning or late afternoon), whereas the volatility of net energy demand is reduce at a considerable extend. For instance, from 481kWh to 320kWh in case 2, or from 529kWh to 300kWh in case 3, i.e. a reduction in changes around 30% to 40%. With only a DR controllable load the maximum changes in net energy demand (around 10%) are reduced to 5-6%, improving customer performance from the point of view of Power System.

TABLE I. DR/DSF RESULTS

Index/ratio (daily)	**Case 0: avg. PV**	**Case 1**	**Case 2**	**Case3**
Daily peak with PV (kW)	318	318	311	353
Daily peak with DR (kW)	NA	316	316	331
PV generation (kWh)	971	1035	770	254
Load (baseline, kWh)	5398	5398	5398	5398
HVAC energy (kWh)	1843	1813	1759	1541
Daily change in energy without DR (kWh, %)	NA	335 (6.2%)	481 (8.9%)	529 (9.8%)
Daily change in energy with DR (kWh, %)	NA	249 (4.6%)	320 (5.9%)	300 (5.5%)
Comfort (max and min temperatures, ºC)	19-18.6	20-17.8	20-17.7	20.5-16.8

IV. CONCLUSIONS

Medium segment of customers and specially buildings can obtain interesting benefits from RES self-generation and energy management through DR, alone or with the help of an aggregator. Unfortunately, it is difficult to participate in the electricity markets with DR alternatives, and self-generation with PV is difficult in some countries, but the future seems promising. This paper presents improved methods for both actors (customer and aggregator) to understand, evaluate and overcome some barriers for PV and DR in the markets, establishing interesting synergies amongst both resources. The advantages of this approach are: the universality of PBLM models for loads, the analysis and consideration of customer service (internal temperature in the case of HVAC), and finally the balancing of PV generation, and its volatility in some periods. Through these tools and taking profit from future electricity markets and enabling technology, the deployment of PV and DR become easier and this will be valuable for price response and the economic management of ancillary services in the short and medium term.

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