Integration of Distributed on Site Control Actions via Combined PhotoVoltaic and Solar Panels System

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Abstract-- **A systematic evaluation of the potential energy saving and CO2 emissions reduction on buildings was carried out, when a renewable energy system is locally installed. The exploitation of a combined solar and photovoltaic system and the integration of suitable energy management actions were deeply investigated. A model of these solar and photovoltaic components has been developed and included within a complete house simulator, capable to precisely figure out the daily electric energy consumptions of typical apartments and to measure the positive actions induced by the added renewable energy. Saving up to 40% on the energy consumptions and even more savings on wiring losses seems to be easily obtainable.**

Index Terms— **Energy management, Household appliances Photovoltaic Power system, Solar Power generation.**

I. INTRODUCTION

Global warming and energy demand are nowadays becoming one of the major issues of the third millennium, mainly because human activities seem to have a clear impact on the raise of CO2 emissions as never it has been experienced in the past. Among the different factors affecting this CO2 emissions, energy demand from buildings constitutes one of the most important actors of the described scenario. Energy management actions can reduce the net energy request and minimize consumption peaks at house level, by using a distributed control over every house [1]. These local actions can greatly help to reduce the impact on the global CO2 emissions.

Two different types of energy management control actions can be addressed to accomplish the energy management aims: the Power Levelling (PL, also named Load Shifting control action) which reduces the electrical energy losses inside apartments and the Distributed on Site control actions (DoS) that reduce the electrical energy consumptions. The former energy management control actions shift the household appliances turning on/off instants in order to flat the electrical apartment load profile [2]. The DoS goal is obtained instead by exploiting a local energy production obtained from solar radiation.

The PL actions, implemented with smart shifts of the power loads of household appliances (washing machines, dishwashers, electric storage water heaters, etc), in order to mitigate peaks power request, have two direct advantages: a Joule losses reduction on the wiring system and a temporal flattening of the requested electrical power by considering all the apartment appliances as a whole [1]. The DoS actions are devoted instead to reduce the electrical energy consumptions inside the apartments and, consequently, realize a significant reduction of the related CO2 emissions too. Moreover, CO2 emissions reductions can be obtained by directly reducing the electrical energy demand to the National Utility. The Distributed on Site control actions here proposed are linked to the capability of energy production inside every apartments, by installing PhotoVoltaic (PV) panels, for electric energy production, and Solar Panels (SP) for hot water production. These local energy generators significantly affect the annual energy request and turn out in an immediate money saving return for the end-user too.

In order to evaluate the annual electrical energy consumptions in a typical apartment, with and without the application of the above mentioned control actions, a tailored house simulator has been developed by using a Matlab environment.

As it is described in section II, the house simulator deals with different input variables; some of them in particular must reflect the usual habits of a generic end user that is intrinsically random and can be studied from a statistical point of view by adopting a probabilistic approach [2–7]. In the same section the implementation of the energy management control actions is presented; in section III instead a simplified model of the local energy generators is illustrated, together with the hypotheses on the working conditions of the household appliances. A description of the house simulator results are given next and some conclusion are finally drawn.

II. HOUSE SIMULATOR AND STATISTICAL APPROACH

In order to evaluate instantaneous domestic power consumptions and losses, a house simulator has been developed. The simulator is able to deliver accurate numerical data and to consider a number of different input scenarios which cover the behavior of houses using traditional appliances, houses with intelligent appliances, and houses capable of implementing the above mentioned Distributed on Site functionalities.

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In our simulator a Monte Carlo method was used to obtain more realistic results. This approach is necessary since different houses (or even the same house in different days) exhibit different usage patterns of appliances and loads. Therefore, in order to realistically calculate power peaks and losses, which arise from the appliances' simultaneous activations, it is necessary to execute a huge number of simulations using stochastic inputs. These inputs (e.g. usage patterns or number of activations per day) can be statistically characterized by means of statistical data or surveys in order to closely reproduce users' behavior and customs. The inputs taken into account and the outputs delivered by the house simulator are graphically depicted in Fig. 1 and listed as follows:

- House type and plan (popular, middle-class and luxurious);
- Characteristics of the house wiring (topology, cables lengths and sections, loads distribution among the different circuits, etc);
- Number of inhabitants;
- Typical days of the year (summer working, summer not working, winter working, winter not working);
- Household appliances (Dish Washer, Washing Machine, Electric Ovens, Dryers etc) with their electric load profiles;
- Probability of presence of each household appliance in each house;
- Number of uses of the household appliances per each typical day;
- Different power consumptions of some devices (e.g. air-conditioners, electric ovens, dishwashers) in different working conditions;
- Different power consumptions of same appliances made by different producers;
- Household appliances stand-by consumptions;
- Usage probability.

Even if a deep explanation of the house simulator is out of the scope of this paper (it has thoroughly been described in [8, 9]), it is important to point out that the simulator is able to evaluate: the instantaneous power, the energy consumption and the in-house power losses with an update time interval of 10 minutes. These parameters are evaluated for the whole 24 hours of a chosen typical day (summer working and not working days and winter working and not working days) brings in fact different habits to the house.

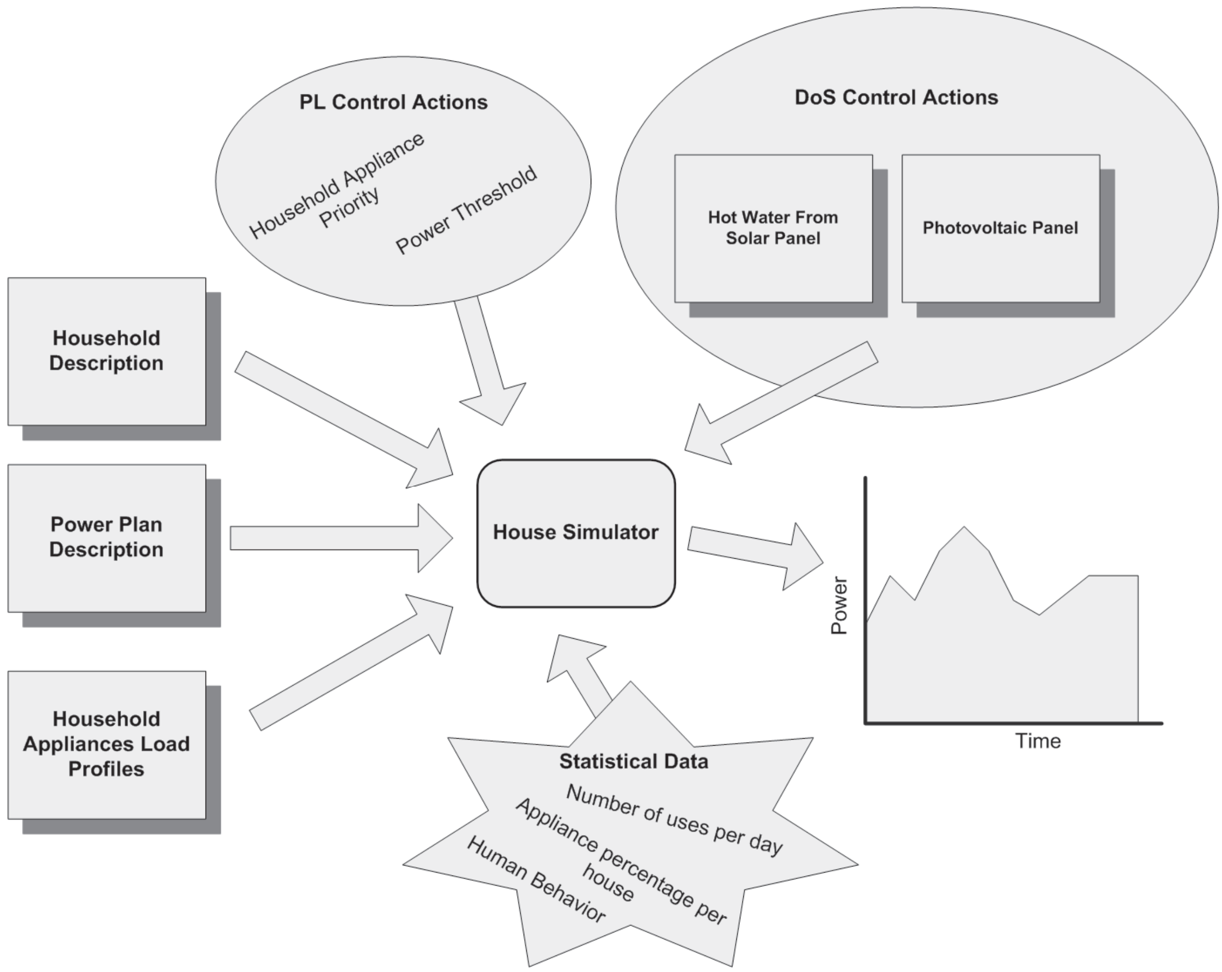

Fig. 1: The house simulator flow diagram.

The two above mentioned control actions are defined within this framework: the power levelling intelligent on/off control actions and the Distributed on Site control actions, both executed by running the house simulator. The intelligent on/off actions work according to the following rules:

- the instantaneous house power consumptions must be lowered by shifting activations of appliances in periods with cheaper energy costs and/or less global request, while maintaining the instantaneous house electric load under a contractual maximum limit, if any;
- the apartment must optimize the energy request from PV panels and/or from hot water tank, by suitably shifting the appliances turning on points;
- appliances priorities must be implemented by classifying them on how long the activation can be delayed without upsetting the user.

The DoS control actions consist in the participation of other electrical form of energy used to satisfy hot water requests, such as instantaneous gas water heater or, as in the case of this paper, a Solar Panel and a hot water tank acting as a storage element.

As already said, the stochastic behaviour has been described via Monte Carlo model, as reported in scientific literature [2,3,4], and the result is represented by using a graph reporting the time of the day in which it is likely that the household appliances are turned on.

As an example Figure 2 refers to a typical summer working day and shows the normalized daily probability of some appliances. It's clear that the washing machine activation probability is quite high between 7 AM to 9 AM, while the dishwasher and the bathroom lighting activation probability is bigger than 10% after 8 PM only.

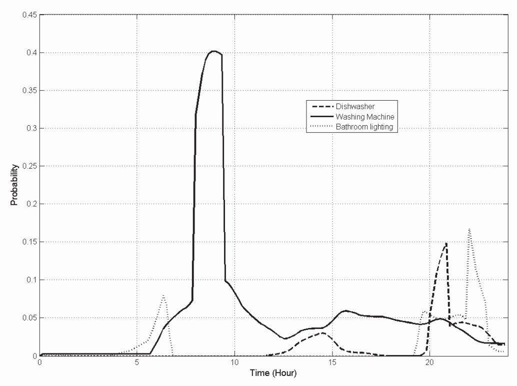

Fig. 2: Household appliances activation probability.

According to the above defined probability, the house simulator can possibly allocate a specific load profile, different for each appliance, if and only if the appliance will be effectively switched on. Every load profile has a particular duration (T_d), during which the *J-th* household appliance is actually consuming energy, and the related absorption function $P_J(\tau)$ is defined by the following equation:

$$P_J(\tau)=\begin{cases} f_J(\tau) & T_i<\tau<T_i+T_d \\ 0 & \textit{otherwise} \end{cases} \qquad (1)$$

being $f_J(\tau)$ the load profile of the *J-th* appliance, T_i the initial time, chosen by the simulator according to the *J-th* appliance's probability, and T_d the power profile duration.

The simulator is able to select a particular switch on instant, for every household appliance, within the 24 hours of a full day and with a time resolution of 10 mins. If the whole house is equipped with N household appliances then the whole stochastic process, defined as "the absorption of electrical energy of the whole house" is described by the function:

$$P_d(t)=\sum_{i=1}^{N} P_i(t) \qquad (2)$$

with $P_i(t)$ representing the i-th absorption function defined in (1).Thanks to this statistical approach and by means of a simulation program implementing the Monte Carlo technique it has been possible to build the whole house load diagram. During all the simulation presented throughout this paper a 4 persons family has been considered and a 100 square meter house equipped with the following different appliances: lighting of all the rooms, PC, Hi-Fi, TV, hair drier, extractor fan, electric shaver, toaster, microwave oven, hood, dishwasher, iron, washing machine, polisher, vacuum cleaner, dryer, electric oven, induction hob, electric storage water heater, fridge/freezer and air conditioner.

The stochastic method has been based on the extraction of a random number, between 0 and 1, for every appliance showing a positive probability function (different from zero) for a particular time of the day. This extracted value is then compared with the activation probability value, expressed by the probability curves. If the number drawn is smaller than the value of the turning on probability then the related appliance load profile is effectively turned on. During the following instants, if the household appliance is on then it is not considered for a new turning on phase. A new turning on phase can happen after a household appliance turning off phase is experienced and also depending on the number of daily usage already matured. Finally on top of this basic behavior, the control actions previously described can vary the initial times of the working condition of the appliances, following the above described rules and if the user will not force an activation.

As regards of the implementation of the above mentioned energy management control actions within the house simulator, new PL and DoS control actions have been here conceived and implemented in Matlab environment.

As for the PL control actions, appliances activation priorities have been related and chosen according to user satisfaction criteria (e.g. if the user wants an appliance to be immediately ready for turning on, it has a high priority), as well as energy efficiency constraints. Activation priority in fact is a measure of how long the activation can be delayed without upsetting the user. De-activation priority refers to the possibility for the apartment ELM (Energy Load Manager) to suddenly turn off the appliance. Of course these parameters are related to user customs and to the particular appliance. These data have been determined for each appliance by considering the user agreement to delay the activation of each appliance and avoiding inefficiency and energy waste.

The highest activation (de-activation) priority has been named A, while the lowest priority C. An appliance with an A priority is not controlled by ELM, but its control is user dependent. If an appliance has got a C priority then activation (de-activation) can be delayed without any constraints. Moreover a intermediate third priority level, named B, has been introduced in order to emulate an appliance activation (de-activation) that can be delayed by the Energy Load Manager (ELM), but only within a specified time interval in order to meet user satisfaction. The intelligent on/off control algorithm is synthesized in the flow graph shown in Figure 3.

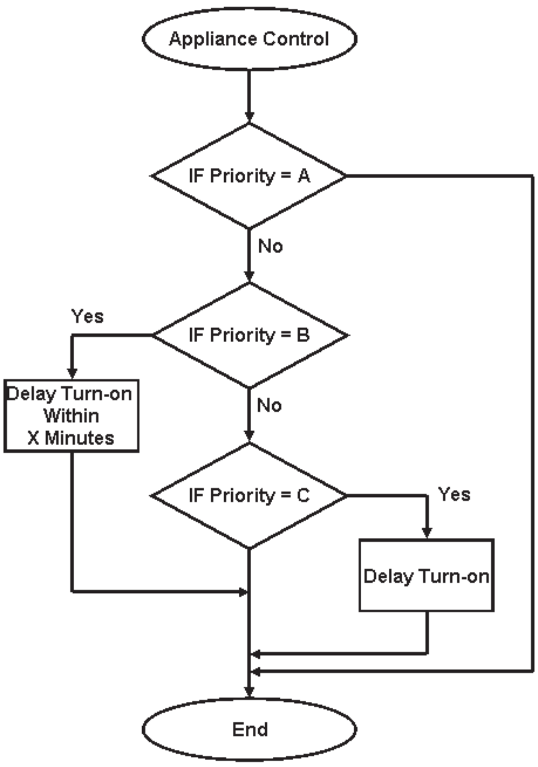

Fig. 3. .The intelligent on/off control algorithm flow graph.

The DoS control actions here proposed are connected to the possibility of locally produce, inside the apartments, energy by installing PhotoVoltaic (PV) panels, for electric energy production, and Solar Panels (SP) for hot water production. The simulator has taken into account these new energy providers, by including within the apartment's power profile a cumulative term related to the instantaneous produced power coming out when the PV and SP are actually working due to the availability of solar irradiation. In particular the thermal energy provided by the SP panel, and stored within a tank, has affected the simulator calculations by introducing a power profile variation of the DW and the WM when these appliances need hot water. Various aspects have been considered in order to simulate the SP and they are more deeply described in the following section.

III. MODELING A COMBINED PHOTOVOLTAIC AND SOLAR THERMAL SYSTEM WITHIN THE HOUSE SIMULATOR

The above described house simulator is also well suited to simulate both PV and SP model in order to estimate the net energy and CO2 saving realized by their use. In particular the starting point of this study has been the real data coming out from a meteorological station located on the authors department's roof, it has routinely collected solar radiation since the last three years. The station is also equipped with a 1 KWp PV panel and the data of the produced electrical power have been directly used to simulate the PV panel behavior and how this panel affect the overall energy consumption during the day both from the lowering of the energy request point of view and from the variation of the shifting actions related to the presence of PV time-variant electrical energy.

In order to simulate the contribution of solar energy coming from the solar panel and stored in a hot water tank, a simplified model of a solar thermal system has been carried out. In particular a forced circulation system with an accumulating boiler, located within the house has been considered. Again the same real solar radiation data updated every 10 minutes has been given as the inputs of the solar model (figure 5 and 6). As for the model of the solar system a 5 m^2 collector panel, with under vacuum pipes and a water recirculation system, has been envisaged. The hot water tank is supposed to have a 300 liters capacity and a maximum temperature of the accumulated water equal to 65°C. For the sake of simplicity a 0° south Azimuth and a 0° tilt has been chosen, even if this is not the optimal case.

Starting from these working conditions, the solar system model has kept into account the amount of stored energy into the hot water tank, the positive contribution coming from collectors and the thermal energy requests coming from the household appliances capable to implement a hot water request. In particular a Dish Washer (DW) and a clothe Washing Machine (WM) has been considered in this study, being the highest thermal energy demanding appliances within the house. The electric energy (E_R) usually needed to increase the DW and WM water temperature is given by:

$$E_R = L_W \cdot C_P \cdot \rho \cdot (T_U - T_{amb}) \quad (3)$$

with:
L_W = Amount of needed hot water [l]
C_P = Water specific heat equal to 1,163 [Wh· kg^{-1} ·K^{-1}]
ρ = Water density equal to 1 [kg/l]
T_U = Appliance's needed Temperature [°C]
T_{amb} = Cold water Temperature [°C]
The hot water tank energy (E_S) stored is calculated starting from the equation (3) as follows:

$$E_S = C \cdot C_P \cdot \rho \cdot (T_B - T_{amb}) \quad (4)$$

with:
C = Tank capacity [l];
T_B = Boiler Temperature [°C].

By using the equation (4) and by replacing the temperature T_B with the maximum boiler temperature it is possible to obtain E_{Smax} that is the maximum storable energy.

The energy captured by the collectors (E_{th}), within a time window Δt, is given by:

$$E_{th} = Q_{SOL} \cdot \Delta t \quad (5)$$

with Q_{SOL} (measured in Watts) being the thermal power supplied by collectors and obtained from experimentally collected data.

The model of the solar system has simulated a hot water request with its corresponding thermal energy amount and, as a consequence, the allocated energy spillages decrease the total boiler available energy that in turn end up with a fall of the water temperature within the hot water tank, whose amount can be calculated by the following expression, derived from (4):

$$T_B = \frac{E_S}{C \cdot C_P \cdot \rho} + T_{amb} \quad (6)$$

Moreover an internal power consumption of the solar system has to be taken into account due to boiler and hydraulic circuit losses. For the purpose of the presented study this value has been fixed to 90W by considering a total thermal jump (between hottest and coldest water available) of 45°C, corresponding to a worst case analysis, due to the boiler location within the apartment.

Both PV and SP systems are synchronously updated with the house simulator and in particular the flux diagram of Figure 4 shows the model's internal logic and its interaction with the simulator by updating the boiler energy content and the standing temperature, matched with the running house requests.

Furthermore the model is capable to produce active actions on the simulator by causing appliances load shift and allowing, in some cases, the complete denial of intelligent appliances, when the boiler temperature do not reach the one requested by the pending service.

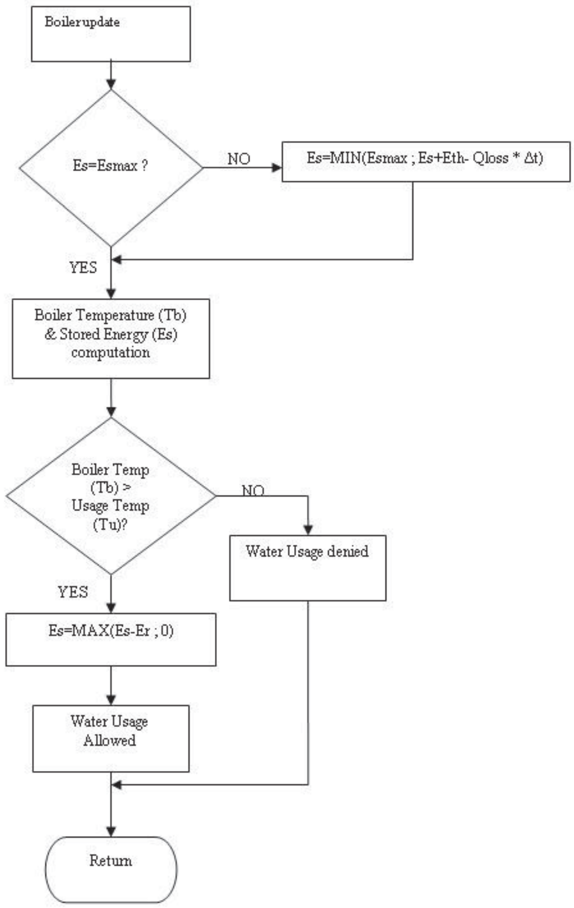

Fig. 4. Flux diagram of the model internal logic

IV. HOUSE SIMULATOR RESULTS

Many trials have been carried out during the simulation campaigns, taking into consideration 1000 iterations of the house simulator for each specified parameter. The above described stochastic approach needs in fact at least 100 iterations of a typical chosen day to get simulated data stabilization. By applying the PV and SP model to the house simulator several interesting results have been found, as described hereafter. First of all, the graphs showed in the following two figures report the real collected data for a typical summer (dotted lines) and winter day (continuous lines) representing the electric PV power and the direct solar power density respectively.

This energy was fed into the house that in turn managed the load shifting actions of all the available loads with the superimposed constraint of using the SP thermal energy for the WM and DW only.

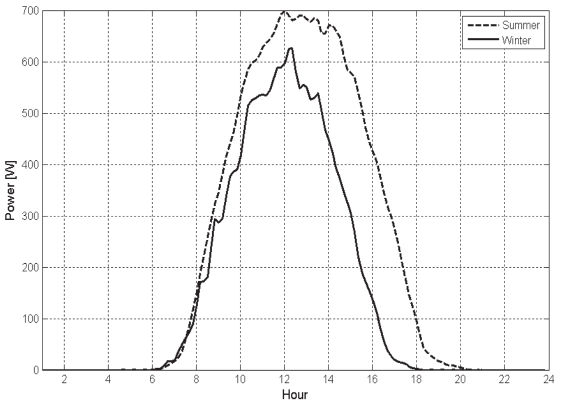

Fig. 5. Daily average distribution of produced electric power for a 1KWp PV panel.

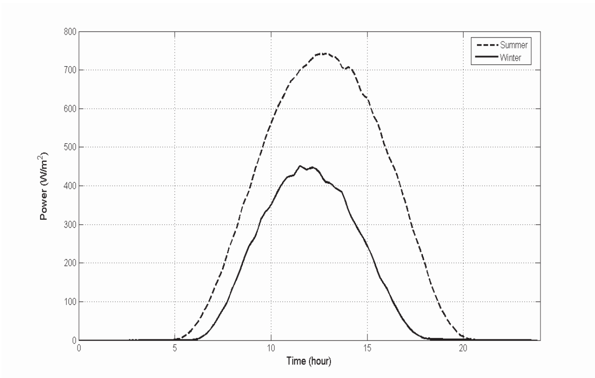

Fig. 6. : Daily average distribution of power density due to direct solar radiation.

These two appliances are supposed to statistically extract two load profiles, a normal and an economic cycle, both having different amount of thermal and electric request as well as different water temperature. Water Temperature (T_{water}) was fixed to 10 °C and 20 °C for winter and summer days respectively. The following table 1 summarizes the main results obtained in terms of estimated energy consumption, daily power peak and wiring losses.

TABLE I
MAIN RESULTS COLLECTED FROM THE HOUSE SIMULATOR.

Simulating Conditions	Average Daily Consumption [kWh]	Daily Power Peak [kW]	Wiring Losses [Wh]
Working summer day Without energy from SP & PV	13.5	3.18	180.0
Working summer day Without energy from PV	10.6	2.30	113.3
Working summer day with energy from SP & PV	8.0	2.23	118.0
Working winter day Without energy from SP & PV	12.5	3.50	154.9
Working winter day Without energy from PV	9.7	2.80	88.5
Working winter day with energy from SP & PV	8.1	2.80	88.5

As it is clear from this table more than 40% saving on the total energy consumption can be easily achieved in both cases (winter and summer days) by comparing the energy request without and with the PV and SP feeding. The power peaks are also greatly reduced, thus allowing a reasonable support of power limited contract by the National Utility Manager. As for the wiring losses, even if they do not reach big energy saving at house level, they actually are of great importance when considering them at city level. They in fact allow the electric distributors to almost halve the distribution losses located within the wiring system. In the above presented simulations, the PV panel energy is effectively used within the apartment and a selling action to the grid has not been considered. Its benefit is quite consistent both in the winter and the summer energy saving, while it does not affect the wiring losses. The Solar Panel system actually decreases the whole amount of electrical energy circulating within the wiring system, thus realizing the wiring losses fall.

Finally a graph depicting the temporal behavior of the house simulator related to the summer working day is shown in Fig.7. In particular the graph is collecting several temporal curves related to different working conditions:

- case A represents the simulation of the energy profile, requested by the house and measured in Watt, when the PV and SP energy terms are not available;
- case B instead is collecting the simulated load when the solar panel is feeding the system with available hot water;
- case C sees a further reduction of the requested energy due to the electric contribute of the PV panel.

Strictly related to these 3 cases is the curve, named “water usage”, which gives the aggregated working density probability of the WM and DW during the 24 hours. It clearly appears that the highest energy consumption periods are related with the use of these two appliances and the stored hot water, obtained from the SP system, works very efficiently in reducing the energy demand peaks. The PV panel energy is instead lowering the house load profile during the central part of the days when its generation is highest.

Finally the case T curve gives the temporal behavior of the boiler temperature (read at the right vertical axis). Despite the water spillages and the internal thermal consumption, this temperature is kept by the collector above 60°C for the all day thus allowing the house simulator to freely choose the initial time of the WM and DW cycles, according with the allowed density probability window described in section II. It has to be finally noted that this temperature behavior leaves room for hot water usage by other appliances but the one considered within this study.

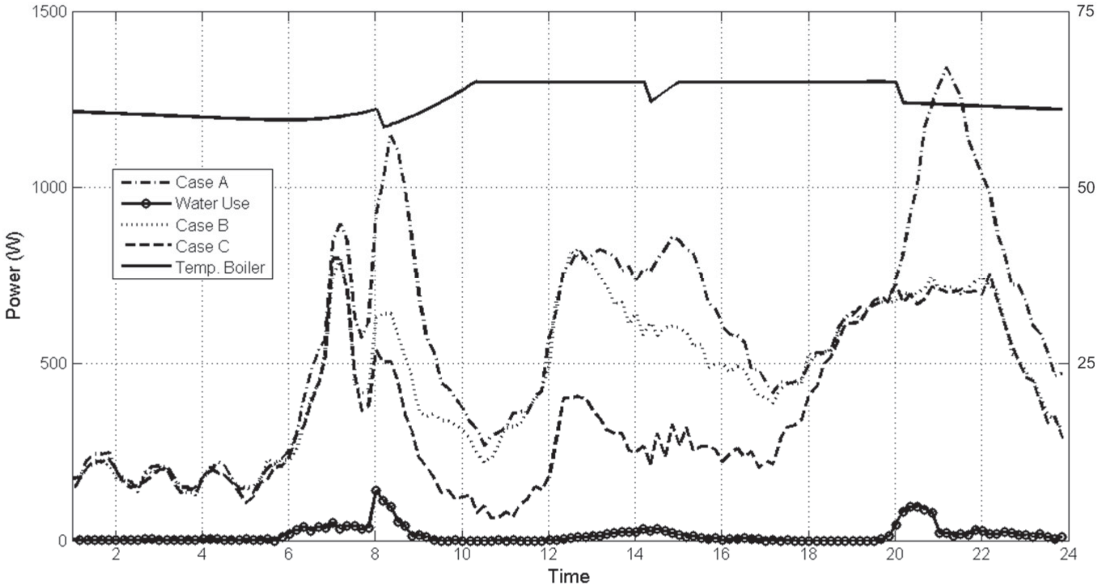

Fig. 7. : Temporal behavior of the house simulator related to the summer working day.

V. CONCLUSIONS

The above described work reports on the investigations carried out within the encouraging field of CO2 emissions reductions, caused by the smart management of buildings' energy consumption profiles. The impact of a renewable energy system has been studied, thanks to , complete in-house developed, house simulator. The stochastic nature of the inhabitants' behavior, the use of intelligent appliances and a model for the renewable system has been integrated within the simulator in order to collect the overall apartments' energy consumptions and wiring losses. Consumptions decreases up to 40% were registered with relation of simulated cases. In addition very encouraging wiring losses cuts were also observed. The working hypotheses on the affecting parameters, considered during the investigations, leave plenty of room to further improve these results and impose an experimental verification of the simulated advantages, that is actually under the authors' on going and planned research goals.

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