House Energy Demand Optimization in Single and Multi-User Scenarios

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Abstract—**With the Smart Grid revolution and the increasing interest in renewable distributed sources, house energy consumption will play a significant role in the energy system: the whole energy generation and distribution system performance can be improved by optimizing the house energy management. Beside the energy bill reduction for single users, another advantage can be obtained for the overall system by jointly managing the energy consumption of a set of users, thus reducing their peak absorption. In this paper we propose optimization models which allow to manage every day energy load for both single and multi-users cases, taking into account distributed energy sources and batteries. Computational results, obtained applying models on real life data, are provided and discussed.**

I. Introduction

In the Smart Grid scenario, residential users are expected to play a key role in improving the efficiency of the network, through the adoption of intelligent mechanisms for managing the energy demand. Home users are indeed responsible for a significant portion of the world's energy needs, but are totally inelastic with respect to the market (i.e. the energy demand doesn't follow the price of the energy itself). In the new Smart Grid a huge amount of data is made available to users such as real-time information on the economic value of energy. At the same time, users have the possibility to send data to the grid, by providing, for example, a feedback on the energy consumption of each home appliance. All these data can be used by demand load management mechanisms, that support residential users in shaping their energy demand profile, with the aim of not only reducing their bills or saving energy, but also using more efficiently the energy itself by means of turning on or off a device in accordance with the electricity grid requirements, moving the peak of the energy demand, or, more generally, shifting the energy behavior of households from intermittent to programmable by defining a power demand profile for the next day and then respecting it in "real-time" during the day. This one will be a real revolution with respect to the social approach to electric energy and will require an effective integration of ICT components into the power grid to make it feasible and comfortable to the final user the effective new opportunities exploitation.

This paper aims at exploiting such new opportunities for users in the future Smart Grid scenario: energy storage devices and renewable sources are considered, as the future domestic environment may be provided with photovoltaic panels and batteries (e.g. electric cars). In particular, we propose a load demand mechanism based on optimization models for automatically managing the daily energy consumption of residential users by means of optimally scheduling home devices activities and deciding when to store\buy\sell energy to the grid. The final goals are to both reduce the user energy bill and improve the overall energy system performance. Two different optimization methods are in particular described:

- Single-User model: the optimization method is used for the optimal planning, for the next day, of a single house energy load ;
- Multi-User model: the optimization method is defined for jointly managing the energy consumption, for the next day, of a group of cooperative users. This model allows the system to easily decrease the aggregated maximum power demand of the group, thus reducing the peak absorption.

The proposed methods, by means of scheduling energy tasks, allow residential users to minimize their bills. At the same time, they automatically ensure the reduction of the electricity demand at peak hours which is a desirable property for the electric grid efficiency.

The remainder of this paper is organized as follows. In Section II we review previous works on demand management mechanisms. In Section III we describe the basic characteristics of the system that we propose for managing the energy consumption of residential users, focusing on the optimization methods that we have defined for planning every day energy loads. Section IV reports some numerical results, obtained using real life data, to evaluate the impact of proposed methods. Finally, in Section V, the paper is concluded and some further developments are discussed.

II. RelatedWork

Recently a great interest has arisen on the electric energy, because of the transition from the old network to the "Smart Grid". The smart grid management, in particular, has been recently introduced in the literature. The importance of optimized management to improve overall system performance is discussed in [1], where an intelligent local controller is proposed in order to manage the operation of a portion of the power system and to coordinate local responses to actual system and market conditions. In the new Smart Grid a huge amount of data is made available to users (e.g. devices power consumption [2], [3]), making it possible to use house energy

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management mechanisms such as the one proposed in [4], where photovoltaic domestic production is also considered: an optimization model is developed and solved to compute the optimal system operation, taking into account the energy market, with the aim of maximizing users profit from selling electricity to the energy market. The overall system performance is not considered and the users loads are not optimized, nor a mathematical description of their consumption is studied. Moreover, a very simplified theoretical market model is introduced, that doesn't correspond to the market models adopted in the EU countries. Renewable energy management has also been considered in [5] where the generation unit is dynamically scheduled based on the intermittent renewable energy power generation situations, stochastic power demand loads, utility cost, reliability and pollution emissions of the generation units. In [6] the problem of adapting house consumption to available energy in tackled via a tabu search algorithm, which decides starting time of services, taking into account energy costs, total energy consumption and unsatisfied services. In [7] a multilevel optimization framework for demand-side load management is presented: the control algorithm provides prediction on the energy consumption and the possibility of adjusting the energy allocation in real time is introduced, to cope with variations with respect to the forecasted energy consumption. More recently, the domestic energy use optimization has been tackled with mathematical models in [8] and with game theory in [9]. However, to the best of our knowledge, the whole house environment, in which loads, generators and batteries, together with market energy prices and availability, are taken into account, has never been considered. Moreover, a parallel analysis between users and grid benefits provided by residential demand management mechanisms has never been fully considered.

III. Demand Management System

The mechanisms proposed in this paper have been designed for managing the electricity consumption and production of a single house or of a group of houses, with the final goals of both minimizing the energy daily bills and improving the efficiency of the whole electricity grid. In the considered scenario, in particular, residential houses are equipped with PhotoVoltaic (PV) panels that produce energy, batteries that allow the system to store energy, and a set of home appliances that have to be used during the day and for each of which a reference start time is provided according to users preferences. Moreover, householders can both buy and sell energy to the market.

The demand management mechanisms are based on optimization models that are in charge of defining the energy plan for the next day, that minimizes the daily bill. Models, in particular, are used for scheduling:

- When to buy, sell and store energy;
- When to start home appliances.

As shown in Figure 1, in order to define the energy plan for the next day, the proposed models require predictions on both PV panels power production and devices future usage. In both cases, learning methods could be defined that based on data collected in the past are able to predict the required information. However, in this paper, we just focus on optimization models in order to evaluate their hypothetical impact on both users bills and electricity grid efficiency. A Graphical User Interface will be developed in the future, for enabling a better user experience of the whole system. These application will enable the display of data and results provided by the optimization models in a simple, effective and intuitive way.

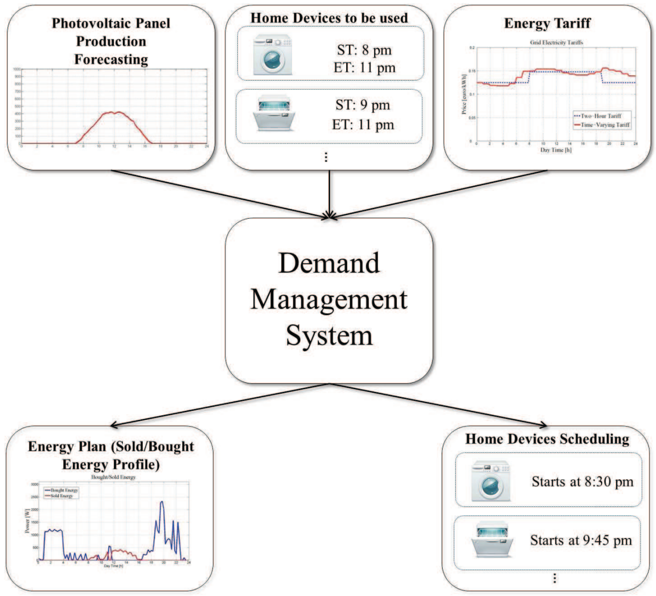

Fig. 1. Demand Management System Operating Diagram.

A. Demand Optimization Models

As said before, we have defined two case study scenarios:

1) Single-User scenario: users autonomously manage their electricity demand; in this case optimization models have to schedule the energy plan of a single house under time-based pricing profiles;
2) Multi-User scenario: users accept to cooperate in managing their energy demands; in this case optimization models are used for scheduling the energy plan of the whole group of users.

In both scenarios the objective function is to minimize the daily bill. Intuitively, by optimally scheduling house appliances activities and managing the power exchange with the network, the user is able to reduce his bill. Nevertheless, in the authors opinion, the economic saving will be not significant for the domestic users (electric energy is a cheap commodity), and another important benefit is correlated with the better exploitation of the electric system: a better coordination of load profiles will avoid peak power demand, postponing investment for the network reinforcement, for new generation plants, and so on. Moreover, the cooperative case allows the system to easily decrease the aggregated maximum power demand of the group of users, giving direct benefit to the electricity grid and indirect benefit to users. All these benefits will fall down indirectly on the final users; their mathematical introduction in the optimization problem is quite complex. For this reason, in the proposed model, we only take into account the direct economic benefit for the domestic user.

B. Single-User Optimization Model

In the considered problem, formulated as an Integer Linear Programming (ILP) model, the 24 hour daytime is divided into 96 time slots of 15 minutes each (set T). In order to schedule house appliance activities represented by the set A, binary variables x_{at} are defined for each activity $a \in A$ and for each time slot $t \in T$, equal to 1 if the activity a starts in the time slot t, 0 otherwise. Besides, continuous non-negative variables z_t and y_t represent the amount of energy sold and bought, respectively, in each time slot t.

Objective function: The goal of the problem is to minimize the daily energy bill. Denoting with c_t and g_t the cost of sold and bought energy in the time slot t, the objective function can be modelled as:

$$\min \sum_{t \in T} (c_t \cdot y_t - g_t \cdot z_t) \tag{1}$$

The first term is the cost of bought energy, while the second one is the gain due to the electricity sold to the grid.

Constraints description:

Activity scheduling: For every activity $a \in A$, associated with a house appliance, a starting time, ST_a, an ending time, ET_a, and a run time nt_a are defined. Constraints:

$$\sum_{t=ST_a}^{ET_a - nt_a + 1} x_{at} = 1 \qquad \forall a \in A \tag{2}$$

guarantee that the activity a starts in exactly one time slot and it is carried out in the required interval (ST_a, ET_a). Notice that the bigger is $(ET_a - ST_a)$, the more the system is flexible in scheduling house appliance activities.

Each activity is divided in phases (set F_a): for each phase of each activity the energy load, lp_{af} is given. Constraints:

$$p_{atf} = lp_{af} x_{a(t-f+1)} \qquad \forall a \in A, t \in T, f \in F_a : f \leq t \tag{3}$$

forces the power in every time slot to be equal to the load profile lp_{af} for that specific activity in that specific time slot.

Batteries constraints: Concerning the batteries, two binary variables ω_{bt}^C and ω_{bt}^D are defined: ω_{bt}^C is equal to 1 if the battery b is charging in time slot t and 0 otherwise, while ω_{bt}^D is equal to 1 if the battery b is discharging in time slot t and 0 otherwise. Such variables are subjected to the following constraints:

$$\omega_{bt}^C + \omega_{bt}^D \leq 1 \qquad \forall t \in T, b \in B \tag{4}$$

so that each battery, in a given time slot, can be in only one of the three possible modes: charge, discharge and off.
The charge and discharge rates are represented by continuous variables v_{bt}^C and v_{bt}^D. Such variables are bounded, for each $t \in T$ according to the following constraints, where τ_b^{max} and τ_b^{min} (and ϑ_b^{max} and ϑ_b^{min}) are the maximum and minimum charge (and discharge) rates, respectively:

$$\begin{aligned} \tau_b^{min} \cdot \omega_{bt}^C \leq v_{bt}^C \leq \tau_b^{max} \cdot \omega_{bt}^C \\ \vartheta_b^{min} \cdot \omega_{bt}^D \leq v_{bt}^D \leq \vartheta_b^{max} \cdot \omega_{bt}^D \end{aligned} \qquad \forall b \in B, t \in T \tag{5}$$

In every time slot, the battery energy depends on the energy of the same battery in the previous time slot, and on the charge and discharge rates, according to the following constraints:

$$e_{bt}^B = e_{b(t-1)}^B + \frac{1}{4}\eta v_{bt}^C - \frac{1}{4}\frac{1}{\eta} v_{bt}^D \qquad \forall b \in B, t \in T : t \geq 2 \tag{6}$$

where η represents the charge/discharge efficiency. For each battery, the energy level is bounded according to the following constraints, where γ_b^{max} and γ_b^{min} are, respectively, the battery capacity and the minimum energy level of the battery required not to damage the battery:

$$e_{bt}^B \geq \gamma_b^{min}, \quad e_{bt}^B \leq \gamma_b^{max} \qquad \forall b \in B, t \in T \tag{7}$$

Finally, for each battery the energy at the initial time slot is set to a given parameter ich_b, which represents the charge level at the beginning of the day, while the initial charge and discharge rates are 0.

$$e_{b1}^B = ich_b, \quad v_{b1}^D = 0, \quad v_{b1}^C = 0 \qquad \forall b \in B \tag{8}$$

Balancing constraint: this constraint forces the balance between the consumed and the produced energy:

$$y_t + \pi_t^{PV} + \sum_{b \in B} v_{bt}^D = z_t + \sum_{a \in A} \sum_{f \in F_a} p_{atf} + \sum_{b \in B} v_{bt}^C \qquad \forall t \tag{9}$$

where π_t^{PV} represents the PV production in the time slot t. Finally a constraint limits the amount of energy that can be bought from the grid, which cannot exceed the Contractual Peak Power (CPP) limits, $\pi_t^{CPP\_IN}$, in each time slot:

$$y_t \leq \pi_t^{CPP\_IN} \qquad \forall t \in T \tag{10}$$

C. Multi-User Optimization Model

In this scenario, a community of users, U, is supposed to cooperate in managing the power exchange with the grid. The resulting optimization model is quite similar to the one described in Section III-B. The objective function, in particular, slightly changes because the goal of the model is now to minimize the global daily energy bill of the group of users:

$$\min \sum_{u \in U} \sum_{t \in T} (c_t \cdot y_t^u - g_t \cdot z_t^u) \tag{11}$$

The first term is the cost of bought energy, while the second one is the gain due to the electricity sold to the grid. Moreover, an additional constraint has to be introduced:

$$\sum_{u \in U} y_t^u \leq \pi_t^{GCPP\_IN} \qquad \forall t \in T \tag{12}$$

This constraint limits the total amount of energy purchased, in each time slot, by the set of users: such value cannot exceed the Global Contractual Peak Power (GCPP) $\pi_t^{GCPP\_IN}$.

IV. Numerical Results

The proposed models have been implemented in AMPL (A Mathematical Programming Language) and solved using CPLEX (an optimization software package from IBM ILOG). In the Single-User problem, the basic configuration that has been considered consists of a residential house having 11 house appliances, connected to the network at the contractual peak power of 3kW. The basic domestic configuration has been obtained from literature data relevant to the Italian standard user [10], while the load profile consumption of each appliance has been defined using the results of a project developed within the Politecnico di Milano [11]. Figure 2, for example, shows the standard load profile associated with a dishwasher, where each time slot corresponds to a period of 15 minutes. Moreover, in Figure 3, we report the statistical distribution of the usage of a washing machine.

Starting from the basic configuration, we have defined multiple scenarios with and without a 1kWp PV panel and a 10kWh/3kWp storage battery, and with different energy cost functions and scheduling constraints. Concerning the electricity prices, two cost profiles have been considered: a two-hour tariff with 15% lower price at the beginning and at the end of the day (i.e. low load hours), and a time-varying tariff where price changes every hour with higher costs at demand peak hours (Figure 4). Both profiles refer to the Italian energy market: the two-hour tariff is the one adopted for residential users, while the time-varying tariff, actually not used, has been computed adding to the day-ahead prices (for a standard 2010 spring day), the costs of electric system ancillary services (i.e. dispatch the electric power, transport and distribution network exploitation, frequency and voltage regulation, power balance and so on). For every tariff, in particular, the price of the electricity produced by panels and sold to the grid is always supposed 20% lower than the price of the electricity bought from the network (20% is a gross estimation of costs of the electric system ancillary services).

As for the scheduling constraints, four scenarios have been analysed in order to represent different flexibility levels of the system in scheduling devices activities: zero, low, medium and high flexibility. Figure 5, for example, shows the medium flexibility scenario. As discussed in Section III, for each appliance a bound has been introduced for both the starting and the ending time (i.e. ST_a and ET_a), representing the period of time in which the device can be used. In Figure 5 both the activity duration (i.e. nt_a) and the interval $ET_a - ST_a$ are represented for each home device considered in our tests. These parameters have been defined with respect to the Italian statistical data available in [10] and [11]. In the high flexibility scenario these bounds have been completely relaxed.

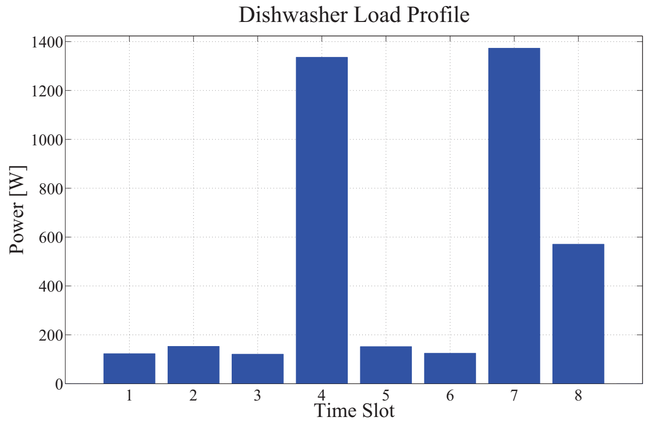

Fig. 2. Dishwasher machine load profile used in our tests.

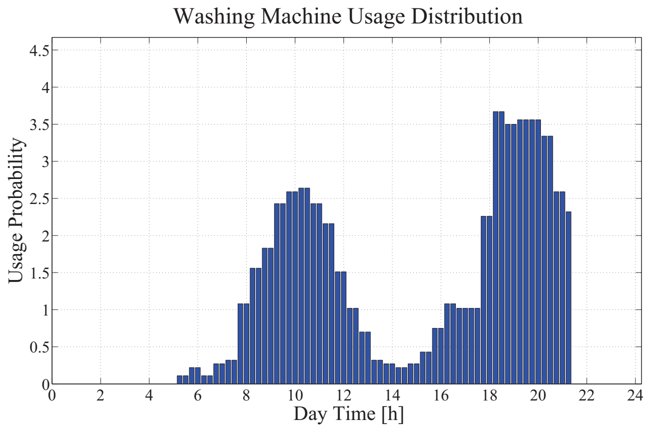

Fig. 3. Statistical data for the use of a washing machine.

The results of our tests are represented in Table I and Table II, where for each battery, PV panel and flexibility combination, the decreasing percentage with respect to the corresponding zero-flexibility daily bill (i.e. the optimization model is not used) is reported. Notice that the theoretical best solutions in terms of bill reduction, for the two-hour and time-varying tariffs, are respectively 15% and 32% (i.e. the decreasing percentage between the most expensive and the cheapest energy price).

Test results show that the performance of the proposed models, as for the two-hour tariff, is just slightly dependent on the flexibility configuration, so that even in the low scenario the achieved improvement is near to the best feasible one, which can be achieved accepting a flexible scheduling. On the other hand, as for the time-varying price, major differences

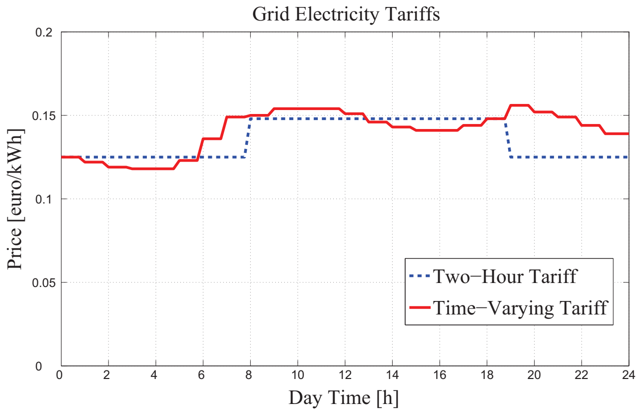

Fig. 4. Price of electricity bought from the grid.

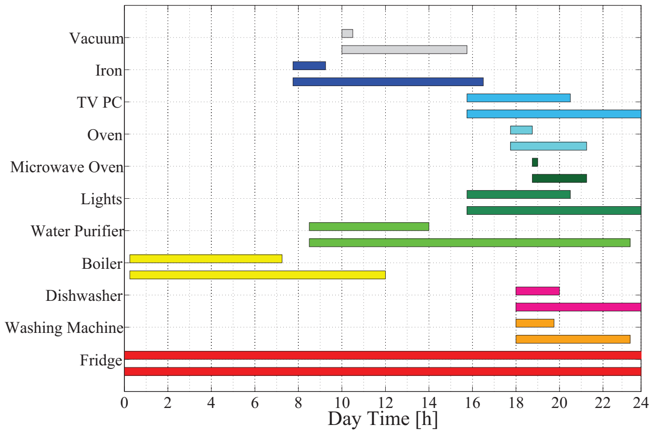

Fig. 5. Medium flexibility scenario considered in our tests.

are shown. In this case, in fact, the flexibility represents a pivotal element for the system to best take advantage of the complexity of the electricity cost profile.

In minimizing the electricity bill, a key role is also played by PV panels and batteries. Panels, in particular, introduce major daily bill decreasing because of the production of additional energy, while a significant saving is also ensured by the battery giving the system the ability to store energy during low-price hours, in order to use it when the electricity becomes more expensive.

One of the main advantages of the proposed model is that it automatically ensures the reduction of the electricity demand during peak hours (i.e. high-price hours), representing an effective distributed demand mechanism for the Smart Grid. In Figure 6, in particular, the electricity demand resulting from the proposed method is compared to that of an unmanaged house, in the two-hour tariff scenario. As it can be seen, the demand during peak hours (i.e. 8 am – 7 pm) is decidedly lower, a desirable property from the distribution electric grid perspective.

For the Smart Grid efficiency, even more benefits can be

TABLE I
SINGLE-USER BILL (WITHIN A 0.05% OF THE OPTIMAL SOLUTION) FOR A TWO-HOUR TARIFF.

		Battery and Panel Configuration			
		0 Bat/0 Pan	**0 Bat/1 Pan**	**1 Bat/0 Pan**	**1 Bat/1 Pan**
Flexibility	**Zero**	1.502 €	1.1661 €	1.502 €	1.1661 €
	Low	-10%	-11%	-12%	-11%
	Medium	-10%	-11%	-12%	-11%
	High	-11%	-12%	-12%	-12%

TABLE II
SINGLE-USER BILL (WITHIN A 0.05% OF THE OPTIMAL SOLUTION) FOR A TIME-VARYING TARIFF.

		Battery and Panel Configuration			
		0 Bat/0 Pan	**0 Bat/1 Pan**	**1 Bat/0 Pan**	**1 Bat/1 Pan**
Flexibility	**Zero**	1.541 €	1.2026 €	1.541 €	1.2026 €
	Low	-5%	-6%	-20%	-23%
	Medium	-5%	-6%	-20%	-24%
	High	-16%	-19%	-21%	-29%

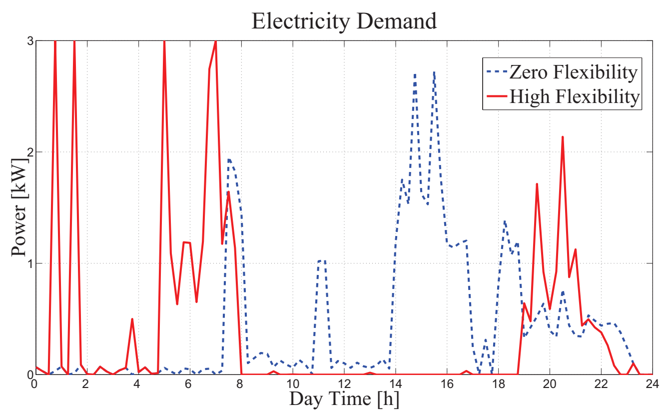

Fig. 6. Electricity demand for zero and high flexibility with a two-hour tariff.

achieved using the proposed method for cooperative groups of users. Cooperation can indeed allow the community of users to reduce its global contractual peak power. In our test we have considered a group of 10 identical houses with 11 appliances each, with different combinations of PV panels, batteries and global contractual peak power. The results for the two-hour tariff and low flexibility scenario are shown in Table III, where for each considered configuration, the increasing price with respect to the corresponding single-user case (i.e. houses daily bills are independently optimized) is reported. Moreover, a demand profile for a particular case is represented in Figure 7.

As it can be seen, the battery represents a key element in order to allow the group of users to reduce its global contractual peak power with a negligible spending increase with respect to the non-cooperative scenario. The same peak power reduction

TABLE III

SINGLE-USER/MULTI-USER USERS BILL (WITHIN A 0.11% OF THE OPTIMAL SOLUTION) FOR A TWO-HOUR TARIFF AND LOW FLEXIBILITY SCENARIO.

	Batteries and Panels Configuration				
	0 B/0 P	**0 B/5 P**	**5 B/0 P**	**5 B/5 P**	**10 B/10 P**
Singe-User, GCPP=30kW, CPP=3kW	13.509 €	11.934 €	13.339 €	11.764 €	10.28 €
Multi-User GCPP=9kW, CPP=3kW	Not Feasible	Not Feasible	+0.003 €	+0.002 €	+0.001 €
Multi-User GCPP=12kW, CPP=3kW	Not Feasible	Not Feasible	+0.001 €	+0.002 €	+0.001 €
Multi-User GCPP=15kW, CPP=3kW	+0.077 €	+0.075 €	+0.001 €	+0.002 €	+0.001 €
Multi-User GCPP=18kW, CPP=3kW	+0.007 €	+0.070 €	+0.001 €	+0.001 €	+0.001 €
Multi-User GCPP=21kW, CPP=3kW	+0.004 €	+0.070 €	+0.001 €	+0.001 €	+0.001 €

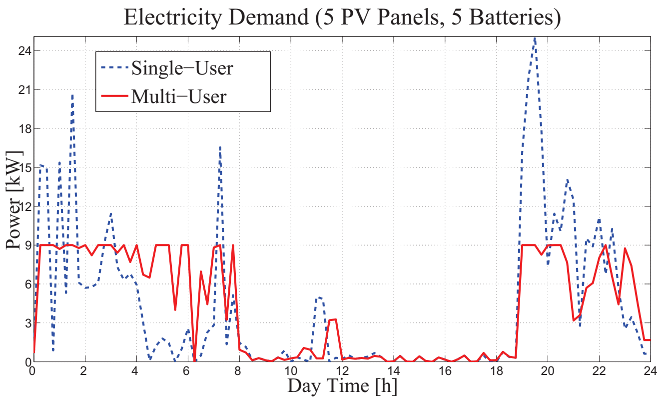

Fig. 7. Single-User and Multi-User electricity demand for low flexibility, 5 PV Panels and 5 Batteries with a two-hour tariff.

would be hardly achieved in the non-cooperative case because it would require the user to significantly change his habits in terms of household appliances usage. People, in fact, could not use multiple appliances simultaneously, unlike to what happens in their everyday life. Notice that reducing the global contractual peak would bring advantages not just to the electric grid, but also to residential users, by means of economical benefits from energy retailers that would be notably higher than the spending increase presented in Table III.

V. CONCLUDING REMARKS

The paper proposed two mathematical models for the minimization of the energy bill of a single user and of a group of cooperative users with respect to a Smart Grid approach. Realistic energy model has been introduced for every appliance, for photovoltaic generation and for a storage device. The electric market has been modelled taking into account two different energy tariff structures: two-hour energy price and dynamic price. The proposed models have been tested on data relevant to the Italian electric market in order to correctly appreciate the performance of each approach. Tests performed confirm the benefits achievable thanks to the dynamic price adoption (greater with respect to the two-hour option), but depict also the electric energy as a cheap commodity, so that by adopting realistic energy prices, direct economic savings will probably not be so important to correctly drive the domestic user towards the proposed Smart Grid integration. Nevertheless, numerical results show a significant benefit for the Electric System, in terms of load peaks shaving and better spreading of the load consumption profile. These Electric System benefits will impact the final user reducing the stress on the electric energy infrastructure (i.e. postponing network reinforcement and/or new power plant), driving to indirect economic savings. The proposed work represents a first step towards an innovative research area that needs to be fully explored and addressed. Firstly, further tests are required for multi-user scenario, in order to evaluate the performance of the model for collaborative groups of heterogeneous users, having different habits and requirements. Another direction for future research is to define advanced versions of the proposed models, allowing devices activities to be interrupted and giving the system more flexibility in managing the electricity demand. Finally, further models should be defined for correctly reacting to real time events that were unexpected or wrongly forecast, trying to reschedule the energy consumption coherently with what had been planned in the off-line stage.

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