Cooperative and Non-Cooperative House Energy Optimization in a Smart Grid Perspective

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***Abstract*—Energy demand management for residential users is a promising research area within the Smart Grid revolution. The whole energy generation and distribution system performance can indeed be improved by optimizing the house energy management while still meeting the energy needs of customers. In this paper we propose Non-Cooperative models for the optimal planning of energy loads of a single house, with the final goal of minimizing the energy bill. A Pre-emptive variant of the model is also presented where some appliances activities can be interrupted in some phases. Finally, Cooperative models are defined for jointly managing the energy consumption of a group of users in order to easily decrease the aggregated maximum power demand, thus reducing the peak absorption. Numerical results, obtained applying models on realistic data, are presented and discussed.**

***Keywords*-Energy optimization; Energy Demand Management; Smart grid; Integer Linear programming;**

I. Introduction

With the increasing share of renewable energies and changes in consumption patterns, intelligent grid management has become a necessity in order to efficiently balance out production and consumption. The energy balance constraint is a specific feature of the electric power system, that has to respond to changes in demand and must be resilient to unexpected events or changes in availability of generation. In the novel Smart Grid the energy balance has become even more a critical issue because of the introduction of renewable sources such as photovoltaic and wind turbines: renewable energy is scattered and decentralised so that electricity doesn't flow from just large central plants to final users as in the classic scenario, but it is actually produced in a discontinuous way, from a large number of sources located in different places. For this reason, in such a scenario, the network management is more and more important for the grid efficiency.

Residential users are expected to play a key role in improving the grid efficiency by means of adopting load demand management mechanisms. Among the more interesting aspects of the Smart Grid are indeed the novel opportunities for domestic users. Worldwide, domestic users cover a relevant portion of the energy needs but are inelastic with respect to the market (i.e. the energy request doesn't follow the price on the energy pool). In the new Smart Grid a huge amount of data is available for users such as information about the "real-time" economic value of the energy or home devices consumption. All these data can be used by load demand management mechanisms that attempt to modify the consumer demand pattern, with the aim of achieving not only bills decrease or energy savings, but also a more efficient use of the energy itself by, for example, switching on or off a process with respect to the electric network energy balance requirements, moving the energy peak consumption, turning the domestic user energy behaviour from intermittent to programmable by defining a power profile for the next day and then respecting it in "real time". This will represent a real revolution and will require an effective ICT integration into the grid to make it feasible and comfortable to the final user.

In this paper we propose a load demand mechanism based on optimization models. Two different methods are in particular described, a Non-Cooperative and a Cooperative method, for the optimal planning of house energy loads for the next day, with the final goal of minimizing the daily energy bill. The Non-Cooperative model intends to schedule house appliances activities, together with the charge and discharge of batteries. Renewable sources impact is taken into account as well, as the considered domestic environment may be provided with photovoltaic panels. A Pre-emptive variant of the model is also proposed where some devices activities can be interrupted in some phases. The Cooperative model has finally been defined for jointly managing the energy consumption of a group of users. This model allows the system to easily decrease the aggregated maximum power demand of the cooperative group, thus reducing the peak absorption. The same result would hardly be achieved in the Non-Cooperative case. By scheduling energy consuming tasks, our methods are able to minimize the cost of energy consumed. Nevertheless, 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 home energy management and load demand mechanisms. In Section III we describe the basic characteristics of the system that we have designed for managing the energy consumption of

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residential users. In Section IV we present two methods for optimizing every day energy loads. Section V reports some numerical results to evaluate the impact of proposed methods. The paper is finally concluded in Section VI.

II. Related Work

In recent years, several efforts have been carried out to design intelligent systems for managing the house energy consumption, giving rise both to commercial projects, such as System Hohm by Microsoft or Power Meter by GOOGLE, and scientific researches. The proposed commercial systems represent solutions for the building automation but, a huge lack is registered with respect to the Smart Grid approach, due to the unavailable interaction with the electric market. Besides, an effort is still requested to users, either in terms of interaction with the market either with respect to the physical use and control of the appliances. In literature many approaches are reported, which try to overcome such drawback. The wide distance between the different point of view has to be correlated to the different energy market structures in place in each country, to the different mix of primary energy source adopted, and on many other factors. The importance of optimized management to improve overall system performance is discussed in [1]: a local controller is proved to take into account and combine local requirements. However, the controller is focused on the distribution electric network and it considers an isolated local portion of the grid. The house environment is considered in many papers. In [2] photovoltaic domestic production is considered: an optimization model is designed to compute the optimal system operation, taking into account the energy market, with the aim of maximizing profit from electricity market supplying. The hourly operating power of sources is optimized. The overall system performance is not considered and the users loads are not optimized, nor a mathematical description of their consumption is studied. Moreover, the theoretical market model that is introduced, is very simplified and not correspondent to the Italian situation (nor to the market structures in place in EU). In [4] the problem of adapting house consumption to available energy is tackled via a tabu search algorithm, which decides starting time of services, taking into account energy costs, total energy consumption and unsatisfied services. In [3] a multilevel optimization framework for demand-side load management is proposed: 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. Domestic energy use optimization has been tackled also with mathematical models in [5] and with game theory in [6]. However, to the best of our knowledge, the whole house environment, loads and generators, has never been considered, together with market energy prices and availability. The cooperative multi-users case scheduling has never been studied as well.

III. Energy Management System

The system proposed in this paper has been designed as a support tool for managing the electricity consumption and production of a single house or of a group of cooperative houses, with the final goals of both minimizing the energy daily bills and improving the efficiency of the electricity grid. In the considered scenario, represented in Figure 1, householders can both buy and sell the electricity to the market. 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. An energy optimization client is finally introduced with the task of scheduling, every day, house appliances activities and power exchanges with the network for the next 24 hours, by means of optimization models. In order to define the energy plan for the next day, proposed models require predictions on both PV panels power production and devices future usage. As for the PV panels, we have defined ad-hoc learning methods that based on weather forecasting, are able to predict the panels production for the next 24 hours. Forecasting algorithms have also been introduced to predict the house load demand (i.e which home appliances will be used and at what time of the day): power meter sensors are used for monitoring the power consumption of home devices [7], [8]; by processing data forwarded by sensors it is then possible to predict load demands for the next day, automatically providing inputs to the energy optimization client exactly in the same way a user could do, thereby improving the system usability and proliferation in the mass market. Based on data forecasts (PV panels production and load demand) and energy tariffs, optimization models define 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 and when to start home appliances.

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

- Non–Cooperative Users: users autonomously manage their electricity demand; in this case optimization models have to schedule the energy plan of a single house;
- Cooperative Users: 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 cooperative users.

In both scenarios the objective function is to minimize the daily bill. Nevertheless, 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. In the following we will focus only on the optimization models that we have defined for managing the energy plan of residential users.

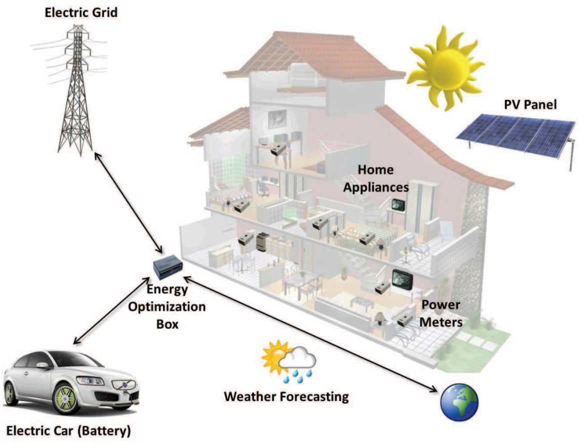

Figure 1. System architecture for a single house scenario.

IV. Energy Optimization Models

In this section we present two Integer Linear Programming models for the minimization of the energy bill of non-cooperative and cooperative users. For both cases we considered a time interval of 24 hours, which is subdivided into 96 time slots of 15 minutes each (set T). The house appliances activities to be scheduled are represented by the set A. Beside, for each activity a a starting time, ST_a, an ending time, ET_a, and a run time nt_a are given. The bigger is $(ST_a - ET_a)$, the more the system is flexible in scheduling activities. As mentioned, users can both buy and sell the energy: let g_t and c_t be the price and cost of energy per time slot, respectively.

A. Non Cooperative Optimization Model

For each activity a and each time slot t a binary variable x_{at} is defined which is equal to 1 if the activity *a* starts in the time slot *t*, and 0 otherwise. Moreover, the amount of bought energy in each time slot is represented by the continuous non negative variable y_t, while the continuous non negative variable z_t represents the amount of sold energy.

Objective function: Using variables y_t and z_t, the objective function minimizing the bill coming from the power exchange with the network, can be modelled as follows:

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

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

Constraints description:

Activity scheduling: Each activity a must be carried out in the interval $(ST_a - ET_a)$, and therefore it must start in exactly one time slot between ST_a and $ET_a - nt_a + 1$, as guaranteed by the following constraints:

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

Each activity is divided in phases (set F): for each phase of each activity the energy load is given. Constraints:

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

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

Batteries constraints: In the considered house scenario, a battery may be present. Two binary variables ω_{bt}^C and ω_{bt}^D are defined to describe the battery charge and discharge: 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. Each battery, in a given time slot, can be in only one of the three possible modes: charge, discharge and off, as guaranteed by the following constraints:

$$\omega_{bt}^C + \omega_{bt}^D \leq 1 \qquad \forall b \in B, t \in T\{0\} \qquad (4)$$

Beside the state of each battery, the charge and discharge rates must be decided and they are represented by continuous variables v_{bt}^C and v_{bt}^D, respectively. 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:

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

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

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

where η represents the charge/discharge efficiency.

Finally, for each battery the energy at the initial time slot must be equal to a given parameter ich_b that represents the initial charge of the battery, while the initial charge and discharge rates are 0.

Balancing and energy constraint: Balancing constraints force the balance between the used and the produced energy:

$$y_t + \pi_t^{PV} + \sum_{b \in B} v_{bt}^D = z_t + \sum_{a \in A} \sum_{f \in F} p_{atf} + \sum_{b \in B} v_{bt}^C \qquad \forall t \in T \qquad (7)$$

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

$$y_t \leq \pi_t^{CPP\_IN} \qquad \forall t \in T \tag{8}$$

B. Preemptable activities

In this model, each activity a is divided into phases of 15 minutes each (set F_a). For each phase f of each activity a the load profile lp_{af} is known. In this case some activities can be interrupted in some phases: single phases must be assigned to time slots instead of activities: a binary x_{atf} is defined for each phase of each activity and for each time slot, which is 1 if phase f of activity a is assigned to time slot t. Constraints must be added to guarantee that each phase of each activity is carried on in the required time interval:

$$\sum_{t=ST_a}^{t=ET_a} x_{atf} \geq 1 \qquad \forall a, f : 1 \leq f \leq nt_a \tag{9}$$

Besides, the model must provide that:

- Each phase is carried on after the previous ones;
- Each activity can be interrupted at most once.

Although activities may be interrupted, the overall amount of energy required by each activity must remain the same as it was in the non-preemptable scenario:

$$\sum_{t=ST_a}^{ET_a} \sum_{f=1}^{nt_a} p_{atf} = \sum_{f=1}^{nt_a} lp_{af} \qquad \forall a \in A \tag{10}$$

C. Cooperative Users Optimization Model

In the cooperative case, a set of users U cooperates with the aim of minimizing their overall bill while reducing the maximum amount of required energy. For each user the optimization model is the one described in Section IV-A. The additional constraints:

$$\sum_{u \in U} y_t^u \leq \pi_t^{GCCP\_IN} \qquad \forall t \in T \tag{11}$$

limit the total amount of energy purchased, in each time slot, by the set of users which cannot exceed the Global Contractual Peak Power (GCPP) $\pi_t^{GCCP\_IN}$.

V. Numerical Results

In our tests all proposed models have been implemented in AMPL and then solved using CPLEX. In order to evaluate the impact of models on both users bills and electricity grid efficiency, we have decided to test them by simulating the other parts of the architecture (i.e. PV production and devices usage forecasting systems), supposing that only correct predictions are provided. In such a way it is possible to assess only the effect of the optimization client, avoiding performance degradation due to missed forecasting.

For the the Non-Cooperative case, we have considered a residential house connected to the grid at the contractual peak power of 3kW and equipped with 11 home appliances. Starting from this configuration, numerous test scenarios have been designed:

- With varying scheduling constraints flexibility level;
- With varying energy cost functions;
- With/without a 1kWp PV panel;
- With/without a 10kWh/3kWp storage battery.

Concerning the scheduling constraints, four different flexibility levels have been defined (i.e. zero, low, medium and high flexibility), representing the grade of freedom of the system in scheduling devices activities. In the zero-flexibility case appliances starting times are just input parameters and not variables of the problem, thereby devices usage can't be optimized. We have attentively defined appliances starting times for this scenario so to represent the habits of typical users in running home devices. This case has then been used as an element of comparison to evaluate the impact of models when appliances optimization is allowed, or rather the flexibility is not zero: in the high-flexibility case, in particular, all the 24 hours are available to schedule devices, while "low" and "medium" represent intermediate scenarios.

With regard to the electricity prices, two types of tariffs have been considered, both represented in Figure 2 and referring to the Italian energy market: two-hour tariff with 15% lower price at the beginning and at the end of the day (i.e low load hours), adopted by Italian residential users; time-varying tariff where price changes every hour with higher costs at demand peak hours. The time-varying profile, that will be introduced in the future, has been computed with respect to real data of Italian day-ahead market. For every type of tariff, the price of buying electricity from the grid is always supposed 20% higher than the price of selling energy to the network, where 20% is just an estimation of the costs of ancillary services.

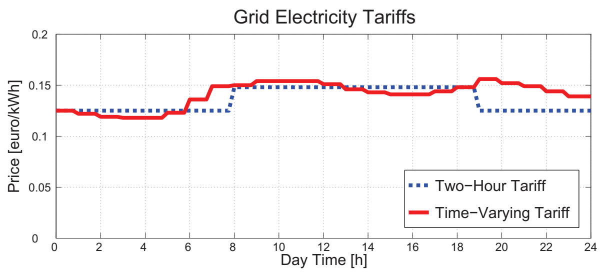

Figure 2. Price of electricity bought from the grid.

The results of our tests, for the Non-Cooperative case, are represented in Table I and Table II, where for each combination of battery, PV panel and flexibility, we report the decreasing percentage with respect to the corresponding zero-flexibility daily bill. Notice that the theoretical best solutions in terms of bill reduction, or rather the decreasing percentages between the most expensive and the cheapest daily energy plans with no constraint on the contractual peak power and on the devices scheduling time, are respectively

15% for the two-hour tariff and 32% for the time-varying tariff. However, in practice, these solutions may not be feasible: they may require to exceed the contractual power limit or to run home devices at times of the day that are actually very different than most people would desire (e.g saving money by turning on the oven at night rather than at 11 a.m. may not be the best idea of your life if you want an oven-baked lasagna for lunch and not for breakfast).

		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 I
NON-COOPERATIVE SINGLE-HOUSE 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**	1.541 €	1.2026 €	1.541 €	1.2026 €
	Low	-5%	-6%	-20%	-23%
	Medium	-5%	-6%	-20%	-24%
	High	-16%	-19%	-21%	-29%

Table II
NON-COOPERATIVE SINGLE-HOUSE BILL (WITHIN A 0.05% OF THE OPTIMAL SOLUTION) FOR A TIME-VARYING TARIFF.

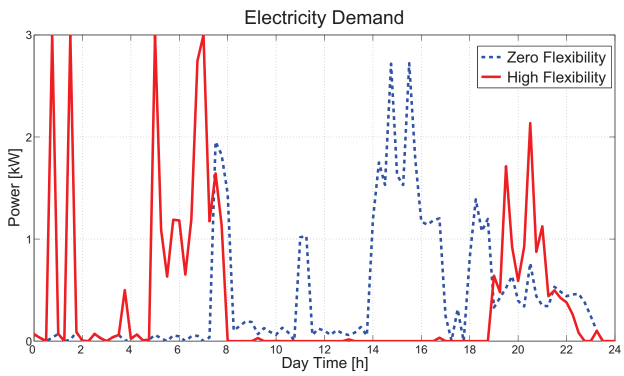

Figure 3. Electricity demand for zero/high flexibility with a two-hour tariff.

As for the two-hour tariff, the bill decrease resulting from the Non-Cooperative model, is just slightly dependent on the flexibility level, so that even in the low scenario the achieved improvement is near to the best feasible one, which can be obtained accepting a high flexibility scheduling. On the other hand, as for the time-varying price profile, major differences are shown: a more relevant saving may be achieved and the flexibility represents a pivotal element for the system to best adapt and take advantage of the shape of the energy tariff. In minimizing the electricity bill, a key role is also played by batteries and PV panels: batteries ensure a bill saving by giving the system the possibility of storing energy during low-price hours, and then using it when the electricity becomes more expensive; panels introduce a major daily bill decrease by producing "free" energy.

An indirect benefit of the proposed model is that it automatically ensures the reduction of the electricity demand at peak hours (i.e. high-price hours), acting as a distributed demand mechanism for the Smart Grid. In Figure 3 an example is reported: the electricity demand resulting from the proposed Non-Cooperative method is compared to that of an unmanaged house. 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.

As described in Section IV, a variant of the basic Non-Cooperative model is obtained by giving the system the possibility of introducing breaks in devices activities. The Pre-emptive models have been tested in the same scenario described above, with a two-hour tariff and a medium flexibility. As reported in Table III, test results show that no benefit is introduced. On the contrary, the problems becomes even more complex and more time is required for CPLEX to find the optimal solution.

	Battery and Panel Configuration			
	0 Bat/0 Pan	0 Bat/1 Pan	1 Bat/0 Pan	1 Bat/1 Pan
Basic Non-Cooperative	1.35 €	1.03 €	1.32 €	1.03 €
Pre-Emptive Non-Cooperative	1.35 €	1.03 €	1.32 €	1.02 €

Table III
SINGLE-HOUSE BILL (WITHIN A 0.05% OF THE OPTIMAL SOLUTION) FOR THE PRE-EMPTIVE MODEL, WITH A TWO-HOUR TARIFF AND MEDIUM FLEXIBILITY.

The last optimization model that we proposed in Section IV is the Cooperative model. The cooperation within a group of users can allow the community to reduce its global contractual peak power, giving direct advantages to the electric grid. However, also residential users would benefit from it, by means of economical advantages. 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 power. The results for the two-hour tariff and low flexibility scenario are presented in Table IV, where for each configuration, the increasing price with respect to the corresponding Non-Cooperative case (i.e. houses daily bills are independently optimized) is reported. Moreover, a demand profile for a particular case is represented in Figure 4. As it can be seen, the battery is 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 would hardly be 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.

	Batteries and Panels Configuration				
	0 B/0 P	**0 B/5 P**	**5 B/0 P**	**5 B/5 P**	**10 B/10 P**
Non Cooperative, GCPP=30kW, CPP=3kW	13.509 €	11,9345 €	13.339 €	11.764 €	10.28 €
Cooperative GCPP=9kW, CPP=3kW	Not Feasible	Not Feasible	+0.003 €	+0.002 €	+0.001 €
Cooperative GCPP=12kW, CPP=3kW	Not Feasible	Not Feasible	+0.001 €	+0.002 €	+0.001 €
Cooperative GCPP=15kW, CPP=3kW	+0.077 €	+0.075 €	+0.001 €	+0.002 €	+0.001 €
Cooperative GCPP=18kW, CPP=3kW	+0.007 €	+0.070 €	+0.001 €	+0.001 €	+0.001 €
Cooperative GCPP=21kW, CPP=3kW	+0.004 €	+0.070 €	+0.001 €	+0.001 €	+0.001 €

Table IV
NON-COOPERATIVE/COOPERATIVE USERS BILL (WITHIN A 0.11% OF THE OPTIMAL SOLUTION) FOR A TWO-HOUR TARIFF AND LOW FLEXIBILITY SCENARIO.

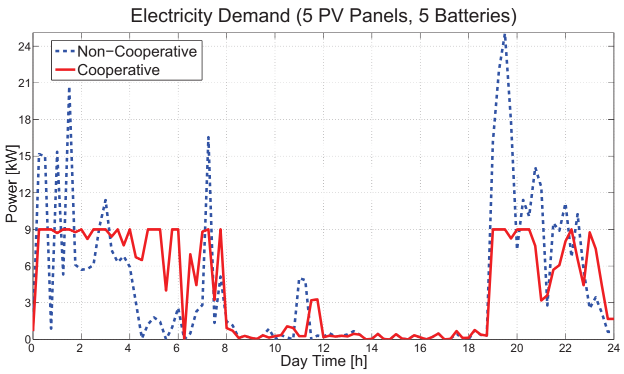

Figure 4. Cooperative and Non-Cooperative electricity demand for low flexibility, 5 PV panels and 5 batteries with a two-hour tariff.

VI. CONCLUSIONS

Traditionally, electric power system was regulated for meeting the combined electrical demand of end-users by increasing and decreasing generation accordingly. Nowadays, the increasing penetration of renewable generators requires a change in this approach, driving the energy demand to be instantaneously coordinated with respect to the production. Such a coordination is widely identified as a cornerstone for an effective exploitation of a green energy approach and requires novel approach to the electric energy commodity. In particular, final users have to change their energy habits with respect to a huge amount of system information. The paper proposed an innovative approach for the single house energy management based on Non-Cooperative optimization methods. Moreover a Cooperative model has also been investigated in order to manage a group of houses. Tests performed depict the electric energy as a cheap commodity: 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, a significant benefit for the Electric System has been obtained in terms of load peak shaving and better spread of the load consumption profile. However, further tests are required for the cooperative scenario, in order to evaluate the performance of the model for collaborative groups of heterogeneous users, having different habits and requirements. Moreover 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.

REFERENCES

[1] A. Chuang and M. McGranaghan. Functions of a local controller to coordinate distributed resources in a smart grid. In *PES General Meeting*. IEEE, 2008.

[2] C. Clasters, T. Ha Pham, F. Wurtz, and S. Bacha. Ancillary services and optimal household energy management with photovoltaic production. In *Energy*, 35(1):55–64, 2010.

[3] L. Duy Ha, F. de Lamotte, and H. Quoc Hung. Real-time dynamic multilevel optimization for Demand-side Load management. In *IEEM '07*, pages 945 – 949. IEEE, 2007.

[4] L. Duy Ha, S. Ploix, E. Zamai, and M. Jacomino. Tabu search for the optimization of household energy consumption. In *IRI '06*, pages 86 – 92. IEEE, 2006.

[5] S. Hatami and M. Pedram. Minimizing the Electricity Bill of Cooperative Users under a Quasi-Dynamic Pricing Model. In *SmartGridComm '10*, pages 421–426. IEEE, 2010.

[6] C. Ibars, M. Navarro, and L. Giupponi. Distributed Demand Management in Smart Grid with a Congestion Game. In *SmartGridComm '10*, pages 495–500. IEEE, 2010.

[7] X. Jiang, S. Dawson-Haggerty, P. Dutta and D. Culler. Design and implementation of a high-fidelity ac metering network. In *IPSN '09*, pages 253–264. IEEE, 2009.

[8] A. Rowe, M. Berges and R. Rajkumar. Contactless sensing of appliance state transitions through variations in electromagnetic fields. In *BuildSys '10*, pages 19–24. ACM, 2010.