Distributed Control Approach for Community Energy Management Systems

Andrea Mercurio, Alessandro Di Giorgio, Alessandra Quaresima
Department of Computer, Control and Management Engineering "Antonio Ruberti"
University of Rome "Sapienza", Via Ariosto 25, Rome, 00185, Italy
{mercurio, digiorgio }@dis.uniroma1.it

Abstract — **In this paper we present a system architecture and suitable control methodologies for the management and control of Distributed Generation (DG) units, Renewable Energy Resources (RES) and Active Demand (AD). Within the proposed platform, control methodologies allow to adapt unit generation profiles and active loads to ensure economic benefits to each actor. The key aspect is the organization in two levels of control: at residential level a Smart Home Controller (SHC) monitors and controls smart appliances while at higher level a Community Energy Management System (CEMS) coordinates generation units, set of SHCs and power grid energy withdrawals. Proposed control methodologies involve the solution of a Walrasian market equilibrium and the design of a distributed algorithm.**

Keywords — Energy Community, Smart Home Controller, Community Energy Management System, Distributed Optimization.

I. Introduction

A radical transformation is in progress and regards a new way of thinking the electric grid. Such modernization is meant to improve energy efficiency, to allow seamless penetration of electric cars, Distributed Generation (DG), Renewable Energy Sources (RES). As well, the availability of technologies enabling the active participation of energy consumers, the so called Active Demand (AD), allows the definition of Demand Side Management (DSM) services. Many research and industrial efforts are ongoing and try to define the functionalities and architectures of next generation Smartgrids, i.e. enhanced distribution grids capable of interacting with AD, DG and RES, in order to allow better exploitation of local energy generation and to offer DSM products to the TSO. The FP7 funded ADDRESS project [1] is one of the most advanced initiatives in Europe that attacks this problem and proposes interesting architectural solutions. As described in [2], the reference architecture is based on: residential Energy Boxes (EB), provided with sufficient intelligence and connectivity means to self-schedule microgeneration and loads; AD aggregators that aggregate the AD on specific load areas (LA) defined over the distribution grid (LA are defined by the DSO using proprietary information); advanced Distribution Management Systems (DMS) taking care of the distribution grid control, interacting with AD aggregators and retail markets. A similar work has been performed within the Italian national research project E-CUBE, which mainly concentrates on defining the architecture and the communication technology basis for a Smartgrid infrastructure capable of controlling and scheduling AD, RES and DG. Such platform is based on two entities: the Smart Home Controller (SHC), being a residential aggregator, and the Community Energy Management System (CEMS), being an AD aggregator. With respect to the ADDRESS project, within E-CUBE DG and RES are considered in the balance of the AD aggregator, and the load areas are named Energy Communities (EC). The aim of this work is to present such architecture and in this paper EC or LA will be named indifferently. The SHC problem has been discussed in [3], [4] and [5]. This paper presents the CEMS problem and proposes a control framework. Network constraints are not considered for ease of discussion and because, as described in the ADDRESS architecture, this task is faced by the advanced DMS and not in the AD aggregators. Nevertheless authors are currently working to include network constraints in the proposed approach. As well, the exploitation of storage means has not been analysed, but authors have presented a solution in [5]. The key aspect of this work is the realisation of a Walrasian competitive equilibrium [7] in a local market of energy, realised within the LA, where the power grid is considered as one of the energy producers. The market equilibrium is found by means of a lagrangian decomposition and the solution of the dual problem that leads to a distributed control mechanism. A strong literature that used the mentioned method is available, mainly from F.D. Galiana, A L. Motto and A. Conejo in [8], [9] and their following works. This paper can be seen as an adaptation to the distribution grid of the concepts elaborated in [8] and [9] for the economic balance of the power system. In particular the following innovations are introduced: the concept of node is replaced with that of LA/EC within which the number of energy consumers is in the order of hundreds; within this paper some proposals for the residential utility functions are made, mainly based on the work performed in [3][4][5]; each consumer and producer of energy participates to the auction mechanisms, therefore there is not a LA/EC marginal price, but rather each producer shows its price to the consumers. A more recent work [10] is concerned with in-house consumption scheduling but the control algorithm proposed at neighborough level is not proven to be optimal.

This work is partially supported by the E-CUBE project, funded by the italian research program INDUSTRIA 2015

The approach proposed in this work tries to solve privacy problems by exploiting a distributed control approach, in which only little information needs to be exchanged, while the control method proposed at EC/LA level is designed to be optimal. Moreover, this work differs from the Microgrid concept [11] as it is not intended to provide autonomous capability to portions of the distribution grids.

The paper is organized as follows. In Section II the overall system architecture is presented. In Section III the models of the controllers are presented. In Section IV control methodologies are presented for the CEMS. Finally, Section V reports the results of simulations.

II. System Architecture

The system architecture (Figure 1) proposed for the management of AD, DG and RES, is based on a residential controller, the SHC, and an aggregator/controller on MV/LV level, the CEMS. The CEMS is meant to provide the fully controllable DG with the generation set-points, the SHCs with price/volume signals based on the generation costs and forecast of generated power from RES. Another task is also to take care of the exchange of information with actors outside the LA. Such a controller can be a central unit which can collect all the needed data and computes the optimal generation set-points and the required price/volume signals implementing distributed control techniques in order to reduce complexities in calculations and avoid privacy issues. The SHC schedules smart loads inside a residential environment according to the specific energy contract, the information collected from the devices in the home domain and the price/volume signal coming from the upper level aggregator. Interested reader may refer to [3][4][5] for a detailed description of the SHC. Within the E-CUBE project, CEMS to SHC communication can be granted by PLC, WIMAX or GPRS technologies; SHC to appliances communication is realized through Zigbee. It is important to note that the SHC's owner is the residential customer, while the CEMS aggregator is managed by a retailer that aims to offer DSM products to the energy market.

III. CEMS Modeling

CEMS domain is constituted of several SHCs, RES and Traditional Power Plants (TPPs), the latter are considered to be every kind of power plants that produce energy by means of fuel consumption and whose set point is controllable. Consider the LA consisting of R users and L energy suppliers. The CEMS main task is to balance energy consumption and generation, trying to guarantee overall fairness, energy producers profit and consumers' expectations. Thanks to the SHC, each consumer can be viewed as an independent entity: the energy demand of each user may vary according to many different factors such as the time of the day, the climate conditions, the price of electricity, user's habits, etc. These different ways of requiring electric energy can be analytically modeled by means of "utility functions" coming from microeconomics [12], which represent the level of satisfaction obtained by the user as a function of its power consumption.

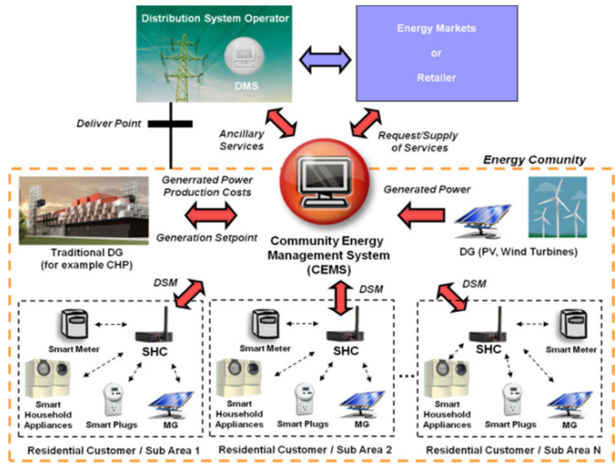

Figure 1. Two levels control for EC/LA

TABLE I: List of symbols

Symbol	Meaning
T	Time horizon, that is divided in 24 time slot [h]
R	Number of EC's users
L	Number of EC's power plants
$x_{rl}(t)$	Amount of power bought by user r∈R from the power plant l∈L [kW]
$\bar{x}_r(t)$	$\bar{x}_r(t)) = [\, x_{r1}(t), x_{r2}(t), .. x_{rl}(t), .. x_{rL}(t)]$
$U_{rl}(x_{rl}(t))$	Utility function related to the user r∈R and the power plant l∈L
$U_r(x_{r1}(t), .., x_{rL}(t))$	Global utility function related to the user r∈R and all the power plants L
$[m_{rl}(t); M_{rl}(t)]$	Minimum and Maximum power consumption for user r ∈R on plant l∈L
$c_l(t)$	Amount of power generated by the power plant l∈L
$C_l(c_l(t)))$	Cost function related to the power plant l∈L
$[c_{min}(t); c_{max}(t)]$	Minimum and Maximum power generation for plant l∈L
$P_r^{max}(t)$	User power threshold [kW]
$p_l(t)$	Lagrange multiplier associated with the power plant l∈L
$y_l^*(t)$	Total power consumption seen by the power plant l∈L [kW]
$P_g(t)$	Energy price of network operator [€cent/kWh]

It is possible to model different behaviours of each user through various choices of utility functions [13]. The generation side is modelled through cost functions indicating the cost of providing a certain amount of energy in a particular time slot. Within this paper, the time horizon T has been divided in 24 time slot t∈T.

Utility functions must fulfill the following properties:

- They are monotonically non-decreasing: the level of satisfaction of each user grows up with the level of power consumption.
- They are concave: the level of satisfaction for users can gradually get saturated.
- They are continuous.

In addition to these basic properties, the task of integrating different energy sources requires that each utility function is a multi-variable function. This allows differentiating the level of satisfaction that each user obtains from an energy supplier instead of one another, essentially due to difference among prices. For each time slot t∈T, each SHC r∈R can define its multi-variable utility function in the following way:

$$U_r\big(x_{r1}(t),\ldots,x_{rl}(t),\ldots,x_{rL}(t)\big)=\sum_{l\in L}U_{rl}(x_{rl}(t)) \quad (1)$$

Where:

- $x_{rl}(t)$ is the amount of power bought from the energy supplier l∈L and that the user r∈R intends to consume during the time slot t∈T. Obviously, $x_{rl}(t)\in I_{rl}(t)$ where $I_{rl}(t)=[m_{rl}(t),M_{rl}(t)]$;
- $U_{rl}(x_{rl}(t))$ represents the level of satisfaction that user r∈R obtains from disposing and consuming $x_{rl}(t)$.

Definition (1) states that the level of satisfaction the user r∈R obtains by disposing of $X_r=\sum_{l\in L}x_{rl}(t)$ is the sum of every single utility resulting from disposing of $x_{rl}(t)$. Microeconomic theory suggests a great number of utility functions that have been widely used in communication and networking literature [14]. In addition to that, recent reports [15] indicate that the behavior of power users can be accurately modelled by certain utility functions, in particular, either *piece-wise linear function* or *logarithmic function*. For example, if the generic utility function is a piece-wise linear function, it can be built by the SHC according to the following relationship (2), where:

- $x_1(t)$ is the minimum power required from those loads that cannot be turned off or delayed.
- $x_2(t)$= $x_1(t)+\varepsilon_1(t)$ is the maximum quantity of power required from the loads that cannot be delayed and it is also the minimum amount of power required from hardly schedulable loads.
- $x_3(t)$= $x_2(t)+\varepsilon_2(t)$ is the maximum amount of power required from hardly schedulable loads and it is also the minimum power required from easily schedulable loads.

$$U_{rl}\big(x_{rl}(t)\big)=\begin{cases}0 & 0\le x_{rl}(t)\le x_1(t)\\ a_1(t)x_{rl}(t)+b_1(t) & x_1(t)\le x_{rl}(t)\le x_2(t)\\ a_2(t)x_{rl}(t)+b_2(t) & x_2(t)\le x_{rl}(t)\le x_3(t)\\ a_3(t)x_{rl}(t)+b_3(t) & x_{rl}(t)>x_3(t)\end{cases} \quad (2)$$

Coefficients $a_1(t)$, $a_2(t)$, $a_3(t)$, $b_1(t)$, $b_2(t)$, $b_3(t)$ can be fixed according to user requirements, but with the obvious requirement that $a_1(t)\gg a_2(t)\gg a_3(t)$ for each t∈T. These quantities can be calculated from the SHC on the basis of historical data of user habits exploiting the knowledge of electric appliances programs and consumptions as specified in [3][4][5]. Another simple way of modeling $U_{rl}(x_{rl}(t))$ is by means of a logarithmic utility function, that is:

$$U_{rl}\big(x_{rl}(t)\big)=w_{rl}(t)*\log(1+x_{rl}(t)) \quad (3)$$

where $w_{rl}(t)$ is a proper weight (that can be equal or different for each power plant) and the argument of the logarithm is $(1+x_{rl}(t))$ in order to take into account that if $x_{rl}(t)=0$ then $U_{rl}\big(x_{rl}(t)\big)=0$. For ease of analysis, in this paper the form (3) is used. The choice of the utility function is also important to define the solving method of the market equilibrium.

Each energy supplier l∈L is described by its cost function $C_l(c_l(t))$ indicating the cost that the energy producer l∈L has to face generating $c_l(t)$ units of power [kW] during the time slot t∈T. Also this function must fulfill the following assumptions:

- A cost function must be increasing in the offered energy capacity;
- A cost function must be convex;
- A cost function must be continuous.

Literature's results allow using a quadratic cost function [15], as it is showed in the following relationship.

$$C_l\big(c_l(t)\big)=\alpha(t)c_l^2(t)+\beta(t)c_l(t)+\gamma(t) \quad (4)$$

Obviously, $c_l(t)\in I_l(t)=[c_{min}(t),c_{max}(t)]$. More complex constraints on generators can be considered [8], affecting the definition of the solving method. In this work such constraints are not considered for ease of discussion.

From a social fairness point of view, it is desirable to utilize the available capacity provided by each energy supplier in such a way that the total utility (the utility of all the users belonging to the community) is maximized and the total cost imposed to all the energy suppliers is minimized. For this purpose, the global problem of maximizing the social welfare can be characterized, for each time slot t∈T, as follows:

$$\max_{\substack{x_{rl}(t)\in I_{rl}(t)\\ c_l(t)\in I_l(t)}}\sum_{r\in R}U_r\big(x_{r1}(t),x_{r2}(t),\ldots,x_{rl}(t),\ldots,x_{rL}(t)\big)-\sum_{l\in L}C_l(c_l(t)) \quad (5)$$

subject to:

$$\sum_{r\in R}x_{rl}(t)=c_l(t)\qquad \forall l\in L\ \wedge\ \forall t\in T$$

$$0\le\sum_{l\in L}x_{rl}(t)\le P_r^{max}(\mathrm{t})\quad \forall r\in R\wedge\forall t\in T$$

$$0\le c_l(t)\le C_l^{max}(t)\forall l\in L$$

where

- $U_r(x_{r1}(t),x_{r2}(t),\ldots x_{rL}(t))$ is defined in (1) and detailed in (2)or (3);
- $C_l\big(c_l(t)\big)$ is defined in (4);
- $P_r^{max}(t)$ is the contractual power threshold related to the user r∈R.

The first constraint assures load balancing for each energy sources, while the second constraint is a "local constraint" that assure that each user doesn't violate contractual limits.

IV. SOLVING METHODS

Problem (5) is a concave optimization problem and it is solved in a distributed manner. The Lagrangian function of the original problem is:

$$L(\bar{x},\bar{c},\bar{p}) = \sum_{r\in R} U_r(x_{r1}(t), x_{r2}(t), \dots, x_{rL}(t)) - \sum_{l\in L} C_l(c_l(t)) - \sum_{l\in L} p_l(t)\left[\sum_{r\in R} x_{rl}(t) - c_l(t)\right] \quad (6)$$

where, $p_l(t)$ are the Lagrange multipliers. Hence, the dual problem is:

$$\min_{p\geq 0} D(p) \quad (7)$$

where

$$D(p) = \max_{\substack{x_{rl}(t)\in I_{rl}(t)\\ c_l(t)\in I_l(t)}} L(\bar{x},\bar{c},\bar{p}) \quad (8)$$

Lagrangian in (6) can be decomposed in a first term regarding the users and in another term regarding the energy suppliers:

$$L(\bar{x},\bar{c},\bar{p}) = \sum_{r\in R}[U_r(x_{r1}(t), x_{r2}(t), \dots, x_{rL}(t)) - \sum_{l:r\in L} x_{rl}(t)p_l(t)] + \sum_{l\in L}[p_l(t)c_l(t) - C_l(c_l(t))] \quad (9)$$

therefore, it is possible to solve the dual problem (7) by decomposing it in two classes of sub-problems. The first one is an optimization problem of the global utility of the users. Each consumer, on the basis of the energy price $p_l^*(t)$, can solve individually his own optimization problem (10):

$$\max_{\overline{x_r}(t)\in I_r(t)} [U_r(x_{r1}(t),\dots,x_{rL}(t)) - \sum_{l:r\in l} x_{rl}(t)p_l^*(t)] \quad (10)$$

assuring that the local constraint $0 \leq \sum_{l:r\in l} x_{rl}(t) \leq P_r^{max}(t) \quad \forall r\in R$ still holds. This relationship states that each user maximizes its own utility function minus the cost imposed by the energy supplier.

Each energy supplier can solve its own optimization problem (11), once it knows the energy price $p_l^*(t)$.

$$\max_{c_l(t)\in I_l(t)} [p_l^*(t)c_l(t) - C_l(c_l(t))] \quad (11)$$

That is, each energy supplier computes the optimal power to generate, according to the price $p_l^*(t)$, assuring that the local constraint $0 \leq c_l(t) \leq C_l^{max}(t) \forall l\in L$ still holds. It is possible to solve the dual problem (7) in an iterative manner using the gradient algorithm [16]. Differentiating the dual function (8) with respect to each $p_l(t)$ allows founding the expression of the gradient:

$$\frac{\partial D(p(t))}{\partial p_l(t)} = -\sum_{r\in R} x_{rl}^*(t) + c_l^*(t) = -y_l^*(t) + c_l^*(t) \quad (12)$$

where $y_l^*(t)$ represents the total consumption of power produced by the energy supplier $l\in$ L. In order to solve (7) the algorithm will move following the anti-gradient direction. The updating rule that will converge to the optimal price for each energy supplier $l\in$ L is:

$$p_l^{k+1}(t) = \begin{cases} p_l^k(t) + h_l[y_l^*(t) - c_l^*(t)\,] & p_l(t) > 0 \\ p_l^k(t) + h_l \max\{0, y_l^*(t) - c_l^*(t)\} & p_l(t) = 0 \end{cases} \quad (13)$$

Where:

- k is the iteration of the gradient algorithm;
- $y_l^*(t) = \sum_{r:r\in l} x_{rl}^*(t)$ is the total load regarding the energy supplier l∈L;
- $c_l^*(t)$ is the optimal amount of power the energy supplier l∈L produces;
- h_l is the step, set according to Armijo's rule.

Looking at (13), it is clear that each energy price grows up when the electric network is overloaded, while it decreases if the request is smaller than the bid. Obviously, each price can never be negative. This is the Walrasian *tatônnement* method to reach market equilibrium [7]. Therefore, at each iteration of the gradient method:

1) *the price $p_l^k(t)$, updated according to (13), is forwarded from each energy supplier* l*∈L to each user* r*∈R;*
2) *each user* r*∈R, on the basis of the energy prices it receives, solves its own optimization problem by computing the quantities $x_{rl}^*(t)$ and forwarding each of them to the relative energy supplier* l*∈L;*
3) *each energy supplier receives $x_{rl}^*(t)$ and computes $y_l^*(t) = \sum_{r\in R} x_{rl}^*(t)$;*
4) *each energy supplier* l*∈L solves its own optimization problem, computing the quantity $c_l^*(t)$;*
5) *the algorithm restarts from point 1, until gradient of dual problem is equal to zero.*

The algorithm terminates when it calculates the optimal price, having assured that the total power consumption is equal to the total power production for each energy supplier.

The flowchart in Figure 2 summarizes the interaction among all the actors at each time slot t∈T. The inclusion of network constraints would require further conditions in (5) that, processed according to the proposed methodology, would result in the presence of other lagrangian multipliers working to assure the respect of network constraint modifying the prices to users and generators.

A. Theoretical framework discussion

A theoretical demonstration of the mathematical formulation presented above will be detailed. In order to assure the correctness of the previous formulation it will be shown that *strong duality* holds which allows solving the dual problem (7) instead of the primal problem (5). Since the primal problem (5) is convex and it is characterized by affine equality constraints, the strong duality holds between problem (5) and its dual formulation (7) in force of the Strong Duality Theorem [16]. Thus, it is possible to obtain the optimal solution of the primal problem by solving the dual problem (7) through the updating rule (13), which incorporates optimal solutions of (10) and (11) problems. Moreover the decomposition of the problem allows each actor to solve the problem locally and therefore implementing the desired technique. This result is useful when extending the approach to include storage means as authors have done in [5]. Within this paper a gradient algorithm has been used even locally, thanks to the differentiability of the utility and cost functions. The convergence of the distributed algorithm to the optimal solution is achieved through the Lyapunov's criterion [18].

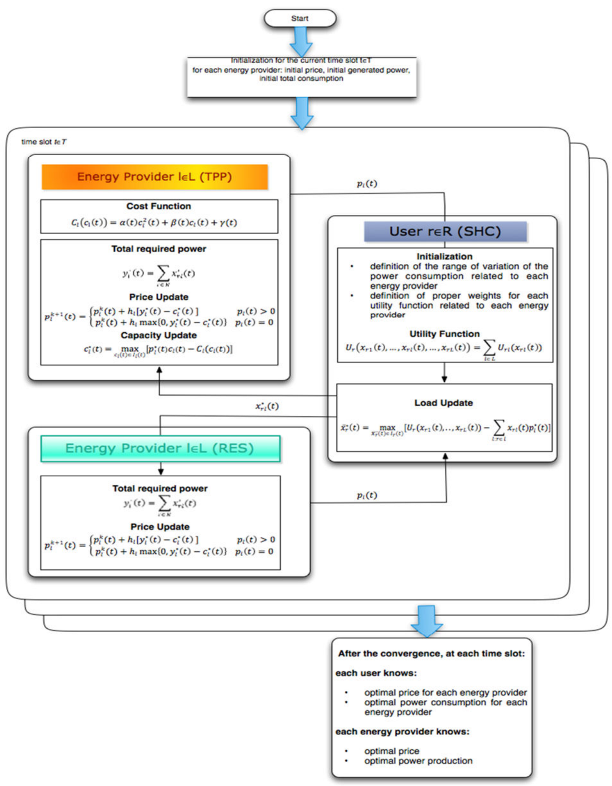

Figure 2: Distributed Algorithm flowchart

It is easy to recognize that the aggregated objective function (5), is strictly concave. Concave optimization [17] assures that there is a unique optimal solution x^* related to the utility functions and a unique optimal solution c^* related to the cost functions. Considering the following Lyapunov function, which results from a proper adaptation to the problem under examination of Lyapunov function reported in literature [20]:

$$V(p) = \sum_{l \in L} (c_l^* - y_l^*) p_l + \sum_r \sum_{l: r \in l} \int_{p_l^*}^{p_l} \left(x_{rl}^* - U_{rl}^{-1}(\sigma) \right) d\sigma - \sum_{l \in L} \int_{p_l^*}^{p_l} \left(c_l^* - C_l^{-1}(\sigma) \right) d\sigma \qquad (14)$$

where:

- The first term inside integral takes into account the utility function particularization (1), which states that each user $r \in R$ will resolve l maximization problems in which $x_{rl}^* = U_{rl}^{-1}(p_l^*)$. Obviously, box constraints on x_{rl} variables are not considered.
- The third term in the summation takes the minus sign coherently with the objective function definition. Also in this case, each power plant $l \in L$ will solve its optimization problem founding the optimal solution $c_l^* = C_l^{-1}(p_l^*)$, without considering box constraints on c_l variables. Differentiating $V(p)$ with respect to time, expression (15) is found. It results that $\dot{V} \le 0$ and $\dot{V} = 0$ only when $y_l = c_l$ or $y_l \le c_l$ with $p_l = 0$. Therefore, the Lyapunov's theorem conditions are verified and the system converges to the unique optimum.

$$\begin{aligned} \frac{dV}{dt} &= \sum_{l \in L} (c_l^* - y_l^*) \dot{p}_l + \sum_r \sum_{l: r \in l} \left(x_{rl}^* - U_{rl}^{-1}(p_l) \right) \dot{p}_l - \sum_{l \in L} \left(c_l^* - C_l^{-1}(p_l) \right) \dot{p}_l = \\ &= \sum_{l \in L} (c_l^* - y_l^*) \dot{p}_l + \sum_l \sum_{r: r \in l} \left(x_{rl}^* - U_{rl}^{-1}(p_l) \right) \dot{p}_l - \sum_{l \in L} \left(c_l^* - C_l^{-1}(p_l) \right) \dot{p}_l = \\ &= \sum_{l \in L} (c_l^* - y_l^*) \dot{p}_l + \sum_{l \in L} (y_l^* - y_l) \dot{p}_l - \sum_{l \in L} (c_l^* - c_l) \dot{p}_l = \\ &= (c^* - y^*)^T \dot{p} + (y^* - y)^T \dot{p} - (c^* - c)^T \dot{p} = \\ &= (c - y)^T \dot{p} = \\ &= \sum_{l \in L} h_l (c_l - y_l)(y_l - c_l)_{p_l}^+ \le 0 \end{aligned} \qquad (15)$$

If piece-wise linear functions were used as utility functions the strictly concavity of (5) would not hold, being piece-wise linear functions not strictly concave, and therefore uniqueness of solution would not have been guaranteed. In that case a sub-gradient [16] method could have been used to assure convergence. More in general, augmented lagrangian methods [19] can be used to face problems that are not locally convex, allowing therefore the use of a wider range of utility functions. Authors are working on such a reformulation of the proposed problem, that would also help to handle the scenarios in which the SHCs consumptions were not continuous variables but discrete.

V. Results

The computational routines to solve the problem have been implemented with MatLab®. The CEMS simulation scenario is summarized in TABLE II. For ease of analysis, it has been assumed that all SHC have the same preferences for the energy generators. The PV power production has been assumed to be the same as Figure 3. The simulation horizon is 24 hours divided in 24 time slots. The energy prices are reported in Figure 4 for each generation unit. The energy cost of the power grid has been formulated in order to let the final price of the power grid to be a typical bi-hourly tariff.

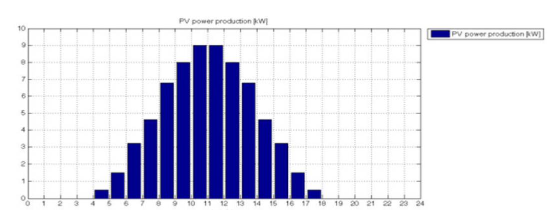

Figure 3. Photovoltaic power generation profile.

Results are very interesting: energy withdrawal from the power grid reduces during the peak hour (Figure 5), the TPP (Figure 6) produces at its maximum and all the energy produced by the PV is consumed by SHCs. The most important result is that the energy consumption of the SHCs is evenly distributed through the whole day at 2kW, avoiding the creation of peak hours, thus intrinsically creating a DSM effect on the consumption. TABLE III summarises the energy saving for the SHCs gained by the exploitation of DG and RES with respect to the use of the power grid only, mainly due to the fact that the TPP presents much lower prices.

TABLE II. CEMS Energy Community Simulation Scenario

N° SHC	20	Logarithmic utility function $\boldsymbol{U_r(x_{rGRID}(t), x_{rTPP}(t), x_{rPV}(t))}$ $\forall \boldsymbol{r} \in \boldsymbol{R}$		
		$x_{rGRID}(t) \in [0; 4.5]$ $x_{rTPP}(t) \in [0; 4.5]$ $x_{rPV}(t) \in [0; 4.5]$ kW Weights $w_{rGRID}(t) = 30; w_{rTPP}(t) = 30; w_{rPV}(t) = 30$ $\forall t \in T$ $0 \le \sum_{l:r \in l} x_{rl}(t) \le P_r^{max} = 4.5$ $\forall r \in R$		
N° “Energy sources” (1=GRID; 2=TPP; 3=PV)	3	GRID cost function	TPP cost function (microturbine Capstone [28 kW]) [€cent/kWh]	RES (PV power plant) [9kW]
		$0.06 * c_g^2(t) + 0.9 * P_g(t)c_g(t)$	$0.02 * c_2^2(t) + 11.4 * c_2(t)$	no cost of production
Initial prices		16 €cent/kWh	12 €cent/kWh	12 €cent/kWh

TABLE III. Energy Savings

	EC with CEMS and local energy resources	**Power Grid Only**
Total bill for a SHC [€/day]	7.79	9.78

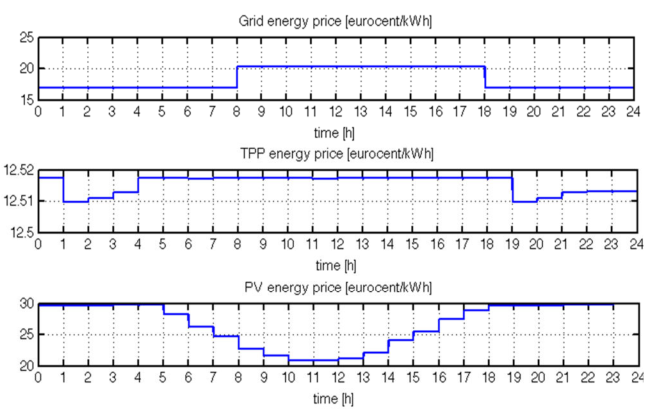

Figure 4. Generation Energy Prices

The total daily bill of user r∈R is computed considering each energy price (Lagrange multiplier) through the following relationship:

$$Bill_r = \sum_{t=1}^{T} x_{rGRID}(t) \cdot p_{GRID}(t) + x_{rTPP}(t) \cdot p_{TPP}(t) + x_{rPV}(t) \cdot p_{PV}(t) \quad (16)$$

The equivalent total daily bill of user r∈R, in case of only power grid withdrawal, is computed considering the power grid energy price as follows:

$$Bill_r = \sum_{t=1}^{T} SHC_{total_{power_{consumption(t)}}} * MainGrid\_energy\_price(t) \quad (17)$$

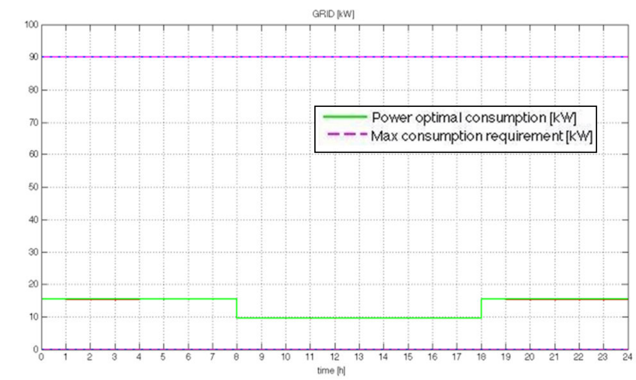

Figure 5. Grid Power withdrawal

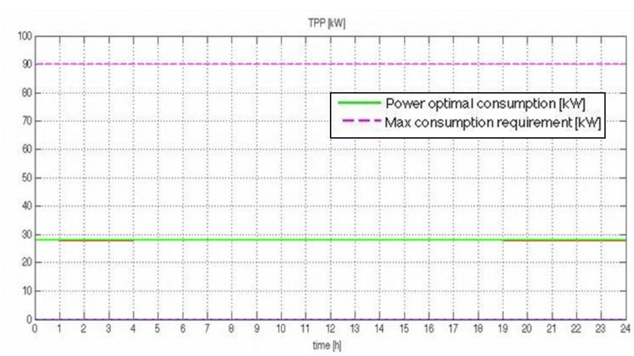

Figure 6. TPP Power Production

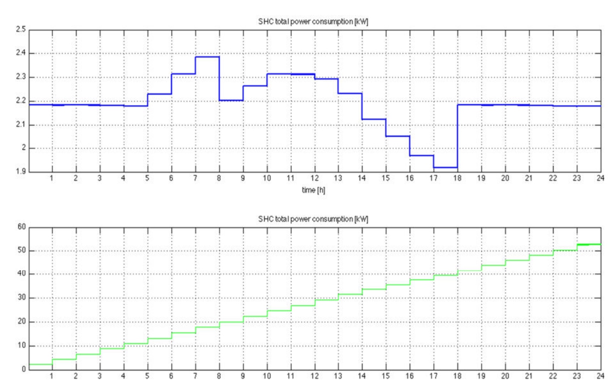

Figure 7. Single SHC power consumption

The total savings for the same power consumption is therefore in the order of 20%. The results show that the choice of the SHC utility functions has a direct impact on overall prices, as expected when the demand is elastic. In particular the price of PV energy is really high and only reduces when the PV increases the production. This is due to the additive nature of the utility functions (1) with respect to energy producers which induces users to request PV energy even though it is not available, hence resulting in high prices when the PV is not producing. The additive nature of the utility functions justifies also that the consumption reduction from the power grid is not due to the production of PV but rather to the price increment during day tariff. SHCs start PV energy consumption as soon as PV produces (around 5a.m.) and increase the consumption during the daytime, this consumption is super-imposed on the other consumptions and is unaffected by the power grid price change. Moreover, if the piecewise utility function were used, the evenly distributed consumption would be somehow limited due to the fact that some loads would be hardly movable within the day; moreover, in the reality, some loads would not be measurable by the SHC. These considerations are fully considered by authors for further developments.

VI. Conclusions

This paper presented the architecture for AD, DG and RES self-scheduling for Smartgrids based on a local controller and an aggregator insisting on a Load Area or Energy Community. Preliminary simulations confirm the capability of allowing the deployment Demand Side Management policies for active demand and the possibility of efficiently integrate Distributed Generation and Renewable Generation. In particular, the proposed algorithm for a cluster of users and generators shows that, besides the realisation of economic savings for users, the energy consumption can be evenly distributed during the day avoiding the creation of peaks of consumption. It has been also highlighted the criticality of the choice of utility functions which affect both the theoretical design of the procedure and the overall results. Currently authors are working to extend this approach to include network constraints and to better define the utility functions for the SHC.

References

[1] http://www.addressfp7.org/.

[2] ”Prototypes and algorithms for network management, providing the signals sent by the DSO to aggregators and the markets, enabling and exploiting Active Demand”, *Deliverable 3.1 of ADDRESS project*, http://www.addressfp7.org

[3] L. Pimpinella, A. Di Giorgio, A. Mercurio, “ Local Energy Management System: Control Scheme and Loads Modeling”, *18th Mediterrean Conference on Control and Automation* (MED 2010), Marrakesh, 22-25 July 2010.

[4] A. Di Giorgio, L. Pimpinella, A. Quaresima, Curti S., “An event driven Smart Home Controller enabling cost effective use of electric energy and automated Demand Side Management”, *19th Mediterrean Conference on Control and Automation* (MED 2011), Corfù, 20-23 June 2011.

[5] A. Di Giorgio, L. Pimpinella, F.Liberati, “A Model Predictive Control Approach to the Load Shifting Problem in a Household Equipped with an Energy Storage Unit”, *20th Mediterrean Conference on Control and Automation* (MED 2012), Barcellona, 3-6 July 2012.

[6] A. Mercurio, A. Di Giorgio, A. Quaresima, “Distributed Control Approach for Community Energy Management Systems in presence of storage”, *20th Mediterrean Conference on Control and Automation* (MED 2012), Barcellona, 3-6 July 2012.

[7] K.J. Arrow and F.H.Hahn, General Competitive Analysis. San Francisco, CA: *Holden-Day* 1972.

[8] F. D. Galiana, A. L. Motto, A. J. Conejo, and M. Huneault, “Decentralized nodal-price self-dispatch and unit commitment,” in *The Next Generation of Electric Power Unit Commitment Models. ser. Int. Series on Operations Research and Management Science, B. F. Hobbs, M. Rothkopf, and R. P. O’Neil*, Eds. Norwell, MA: Kluwer, 2001.S.

[9] A.L. Motto, et al, “ On Walrasian Equilibrium for Pool-Based Electricity Markets”, *IEEE Transactions on power systems*, vol 17, No. 3, August 2002

[10] Kishore, L.V. Snyder, “Control Mechanisms for Residential Electricity Demand in SmartGrids”, *Smart Grid Communications (SmartGridComm), First IEEE International Conference on*, pp 443 - 448 , 4-6 Oct. 2010

[11] Lasseter, Akhil, Marnay, Stephens, Dagle, Guttromson, Meliopoulos, Yinger, and Eto, “White Paper on Integration of Distributed Energy Resources: The CERTS MicroGrid Concept”, CERTS, 2002

[12] H. Varian, "Microeconomia", Cafoscarina, 2002

[13] M. Fahrioglu, M. Fern, F. Alvarado, "Designing cost effective demand management contract using game theory", *in Proc. of IEEE Power Eng. Soc. 1999* Winter Meeting, New York, NY, Jan. 1999.

[14] Low, Lapsley, "Optimization flow control I: Basic algorithm and convergence", *IEEE/ACM Trans. on Networking*, vol.7, no. 6, pp. 861-874, Dec. 1999.

[15] Samadi, Mohesnian-Rad, Shober, Wong, Jatskevich, "Optimal real-time pricing algorithm based on utility maximization for smart grid", S*mart Grid Communications (SmartGridComm), First IEEE International Conference on*, pp 415 - 420 , 4-6 Oct. 2010

[16] D.G. Luenberger, “Linear and Nonlinear Programming”, 3rd Ed. 2007, *Springer.*

[17] Boyd, Vandenberghe, "Convex Optimization", *Cambridge University Press*, 2004.

[18] H.K: Khalil, "Nonlinear Systems", *Upper Saddle River*, NJ: 2nd edition, Prentice Hall, 1996.

[19] A. Ruszczynski, “On convergence of an Augmented Lagrangian decomposition method for sparse convex optimization,” *Mathematics of Operations Research*, vol. 20, pp. 634–656, 1995

[20] S. Shakkotai, R. Srikant, “Network Optimization and Control”, *Foundations and Trends in Networking* Vol. 2, No. 3 (2007) 271–379 2008 DOI: 10.1561/1300000007