# A COLLABORATIVE DEMAND-SIDE MANAGEMENT SCENARIO FOR LIBERALIZED SMART GRIDS

Martin HUPEZ
Electrical Power Engineering Unit,
University of Mons – Belgium
martin.hupez@umons.ac.be

Zacharie DE GRÈVE
Electrical Power Engineering Unit,
University of Mons – Belgium
zacharie.degreve@umons.ac.be

François VALLÉE
Electrical Power Engineering Unit,
University of Mons – Belgium
francois.vallee@umons.ac.be

## *ABSTRACT*

*Following the emergence of the Smart Grid concept, numerous Demand-Side Management scenarios have been proposed in the literature and studied by the actors of the electricity supply chain. However, many of these approaches lack the consideration of the liberalization that the energy markets have undergone or will experience in the near future. Besides, many solutions fail to address the bigger picture of implementing coherent solutions among the actors that serve ambitious policies, leading at times to local optimization behaviors. We propose a scenario that enhances the cooperation potential, through the communication infrastructure and the Smart Meters, based on a day-ahead Energy Consumption Scheduling. The scenario aims at minimizing both commodity and network costs by applying distinct tariffing schemes.*

## INTRODUCTION

The liberalization of the electricity markets and the underlying multiplication of actors in the energy landscape have significantly complexified the coordination efforts needed for carrying the energy transition envisioned for the sector [1]. Yet, there is a pressing need in implementing and deploying ambitious solutions due to the multiple and urgent crises we face, affecting concurrently the environment, the economy and the society at a large scale.

Beyond incentivizing Energy Efficiency (EE) measures, Demand-Side Management strategies [2]–[4] help greatly at leveraging the potential of renewable and Decentralized Energy Resources (DERs) by changing the paradigm between production and consumption of electricity. Instead of adapting the production to the consumption, which implies to rely on generation plants often running on non-renewable resources, the demand-side, by consenting some consumption flexibility, can benefit from cheaper and/or renewable resources such as solar and wind energy. These strategies focusing on load shifting, peak shaving or direct load control are known as Demand Response (DR) techniques [5]–[7].

In order to attain a global and meaningful optimized solution, it is central to reflect the real cost of the energy supply chain. The variables of time and load should be therefore considered in the approach. Besides, the framework should give the opportunity for consumers to collaborate, hence avoiding individualistic and blind optimizations that lead to overall suboptimal solutions (e.g. individual islanded microgrid). The difficulty of a liberalized context relies in the fact that the groups of consumers are different for each actor. Hence, the users of a defined network can be supplied by different energy suppliers. An efficient strategy should coordinate all the users despite their conflicting interests.

In that respect, this work investigates a Demand-Side Management scenario for Low Voltage network users enhancing, on one hand, the collaboration between customers of a same supplier to reduce their commodity costs, and on the other hand, the collaboration of all users of a same network to decrease the network costs by taking advantage of their complementary flexibility. We consider a day ahead Energy Consumption Scheduling (ECS), which consists in programming the operations of flexible loads (e.g. washing machine, dishwasher, electric vehicle…) in order to answer to an objective function [8]–[10]. We use for the objective function distinct aggregated cost curves applying to the commodity costs across the users of a same supplier and a network cost curve accounting for the aggregated load of the network. The suppliers use a Real-Time Pricing (RTP) [11], [12] scheme allowing them to reflect their changing portfolio while the network costs are function of the total capacity. Furthermore, we insure the participation of the users in our DSM scenario by applying a cost distribution of the optimization solution leading to a Nash equilibrium. Finally, we propose a distributed and autonomous resolution of the ECS by using the resources of the individual Smart Meters (SM) and their communication infrastructure in order to guarantee the privacy and the need for a third party.

The next section describes the actors and their interactions in the liberalized context that is assumed. Then, section 3 introduces some mathematical formulation of the Energy Consumption Scheduling problem we wish to optimize as well as its practical solving procedure. In the fourth section, we discuss the outcome of the scenario and its prospects, and finally, section 5 concludes this paper.

We invite the reader to read our journal article [13] for a benchmark comparison of different cooperative scenarios and some complements of mathematical formulation.

## ECS SCENARIO MAP

One important contribution in our proposition is that we assume the context already encountered in many countries that opted for the liberalization of their electricity markets. Hence, we introduce the different actors and their

interactions in such scheme at the level of a Low Voltage distribution network.

## End-users

Low Voltage end-users include mostly residential customers as well as some small and medium businesses. The users can freely choose their energy supplier based on the tariff structure (RTP) they find most suited to their needs. However, only the commodity costs are concerned as the network costs are due to the Distribution System Operator (DSO). The load can be divided in two components:

- Non-flexible load: this is the load for which users do not wish to consent any flexibility (e.g. lighting, cooking appliances, TV, computer…). It can be evaluated or forecasted based on the consumption history and/or with some regression parameters (weather, occupancy…). Local generation facility owned by individuals such as photovoltaic panels can be usually considered as a negative non-flexible load.
- Flexible load: this is the part of the load for which the user grants some scheduling flexibility, usually under some time constraints. The operations of these appliances (e.g. dishwasher, electric vehicle, washing machine) are determined by an Energy Management Device.

The end-users define their electricity needs and their flexibility for the next day through their Energy Management Device, which should be connected or integrated to their Smart Meter in order to access its communication infrastructure. By doing the following, they expect to beneficiate from the lowest possible electricity prices.

## Distribution System Operator

A Low Voltage network is usually owned and operated by a single DSO thus bounding the end-users connected on a same network. Their de facto monopoly is, however, subject to strong regulation by the states. Beside the fixed charges (recurrent maintenance, asset amortization, wages…), a substantial portion of the costs incurred by the DSO is directly related to the network load. The relation between these costs and the network load is not linear (quadratic power losses, increased failure rates under higher solicitation…). Hence, the resulting cost function for the DSO is overall superlinear. As previously stated, passing on an accurate image of the real costs incurred is important. The tariff structure applied to the users should have therefore the same shape of the DSO cost function. That is, a tariff depending on the overall load. In contrast, there is no particular motivation for a network tariff differentiated in time. A uniform network utilization throughout the day is usually incentivized. Besides, DSOs should provide the network with a communication infrastructure between Smart Meters (cf. collaboration and infrastructure).

## Electricity suppliers

Electricity suppliers produce or buy electricity at a continuously varying cost. Depending on their portfolio (generation mix, market auctions), their expenses in function of time can be significantly different. In line with the effort to optimize the real cost of the electricity supply chain, the billing should reflect the incurred costs. A Real Time Pricing structure for the commodity where the next day prices for each period of time are communicated on a day ahead basis is therefore best suited. Suppliers can hence adopt different strategies for their portfolio content to suit more or less different groups of customers.

## Collaboration and infrastructure

The users of a Low Voltage network share common resources. On one hand, all the users share a same network infrastructure and on the other hand, those who have a same supplier share the same commodity source. The underlying groups that are derived can be seen as aggregated entities when billing is applied. Hence, we propose to consider a "network collaborative pool", for which network costs are passed on, encompassing various "supplier collaborative pools" for which the related supplier bills the commodity.

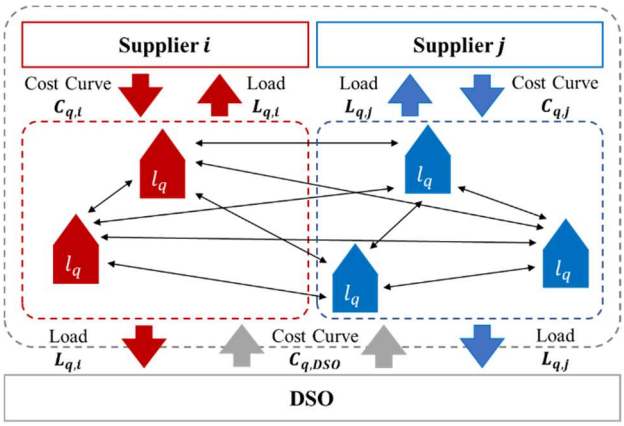


*Figure 1: interactions and communication between the actors of the collaborative ECS*

The Energy Consumption Scheduling and its distributed implementation presented in the next section require mutual communication between all the network users as well as a two-way communication with the respective suppliers and the DSO (cf. Fig. 1). The first enhances collaboration between the users while the second is necessary for the implementation of the RTP and the associated billing. Moreover, the Smart Meters should be associated with an Energy Management Device operating automatically the flexible loads based on the computed schedule.

## SCENARIO FORMULATION

As aforementioned, we refer to our journal article [13] for

the detailed mathematical models and formulation of the energy consumption scheduling. In this section, we emphasize the collaborative scenario objective function to optimize, as well as the cost distribution adopted among the collaborative pools which features a Nash equilibrium.

## Collaborative ECS optimization

### Cost functions

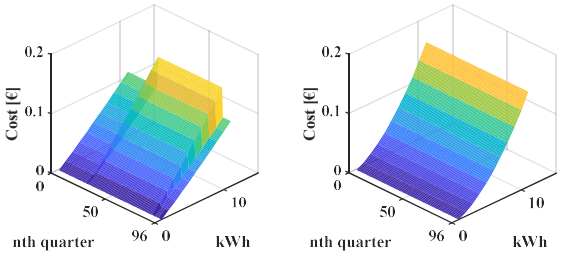


*Figure 2: example of a commodity tariff scheme (left) and a network tariff scheme (right)*

As discussed in, we adopt a Real Time Pricing scheme for the cost of the commodity. As the suppliers hold a certain degree of flexibility on their portfolio and therefore on their cost, we do not consider a capacitive price. Besides, it keeps a better legibility towards the customers who retain their choice of supplier. On the other hand, the DSO does not hold any degree of freedom and the costs incurred are function of the capacity. Hence, network costs are differentiated in the level of aggregated power but there is no differentiation in time (cf. Fig. 2). The cost functions are the following,

$$C_{q,i}(L_{q,i}) = b_{q,i}L_{q,i} + c_{q,i} \quad (1)$$

$$C_{DSO}(L_q) = aL_q^2 + bL_q + c \quad (2)$$

respectively for the commodity provided by supplier $i$ and the network cost applied by the DSO, and where $L_{q,i}$ is the aggregated load of supplier $i$ collaborative pool at time step $q$ and $L_q$ the total load across the network collaborative pool at time step $q$.

### Objective function

The ECS scenario proposed in this paper aims at minimizing the total energy cost. Hence, the collaboration cannot be limited to the collaboration of a few users but instead to all the users of a same network entity; the network collaborative pool. Therefore, it seeks finding the best compromise between commodity costs and network costs. The objective function of the aggregated total cost is thus the following:

$$\min_{x_n \in \chi_n, \forall n \in \mathcal{N}_i, \forall i \in \mathcal{F}} \sum_{q=1}^{96} \left( \sum_{i=1}^{n_s} C_{q,i}(L_{q,i}) + C_{q,DSO}(L_q) \right) \quad (3)$$

where the underlying decision variables $x_n$ are the vectors of flexible consumption determined over the decision set.

### Distributed implementation

In order to keep a higher level of privacy and take advantage of the Smart Meter capabilities, a distributed resolution of (3) can be judiciously applied. It can be shown that if each user at turn solves the following minimization problem, it will converge to the solution of the central problem:

$$\min_{x_n \in \chi_n, \forall n \in \mathcal{N}_i} \sum_{q=1}^{96} \left[ C_{q,i}(l_n^q) + \sum_{j=1}^{n_s} C_{q,j} \left( \sum_{m \in \mathcal{N}_j \setminus \{n\}} l_m^q \right) + C_{q,DSO} \left( l_n^q + \sum_{m \in \mathcal{N} \setminus \{n\}} l_m^q \right) \right] \quad (4)$$

It can be noticed that (4) needs solely the aggregated computed schedule from the other users ($l_m^q$) in order to compute its solution $l_n^q$. Moreover, the schedules do not need to be stored whatsoever. As explained in the following section, only the energy consumption index needs to be communicated to the DSO and supplier for billing.

## Users' billing and ECS game

### Cost distortion and billing

Let's define the following components of the total bill:

- $S_i$: minimum possible commodity cost of the collaborative supplier pool $i$.
- $S_T$: total minimum possible commodity cost.
- $N$: network cost associated to $S_T$.
- $S_i^*$: actual commodity cost (after collaborative optimization).
- $S_T^*$: total actual commodity cost.
- $N^*$: network cost associated to $S_T^*$.

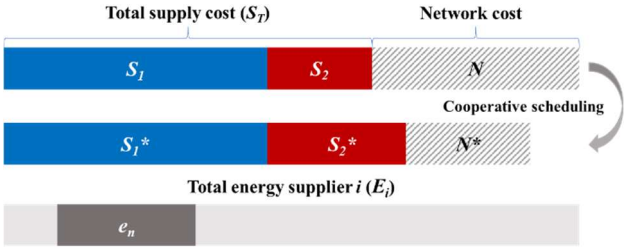


*Figure 3: cost distribution and distortion*

The cost distribution applied when billing the users must insure their participation in the effort of optimizing the total cost. Indeed, each supplier collaborative pool needs to deviate from its optimal solution $S_i$ (cf. Fig. 3) in terms of commodity cost in order to decrease on a greater scale the network cost $N$. Some users will deviate more or less according to what the minimization algorithm finds best, hence leading to a distortion in the relative contribution of each supplier to the total cost $S_i/S_j \neq S_i^*/S_j^*$. In order to enforce a fair distribution, we apply a twofold distribution on the optimized solution:

- Distribution between suppliers according to the proportion between what would be their minimum related cost if their users would schedule only in function of the energy cost and the underlying total commodity cost, that is first fraction of (5).
- Distribution between the users of each supplier proportionally to their fraction of total daily consumption in their respective supplier pool (cf. Fig. 3), that is second fraction of (5)

The daily bill charged ($b_n$) is hence the following:

$$b_n = \frac{S_i}{S_T}\frac{e_n}{E_i}(S_T^* + N^*) \qquad (5)$$

**Nash Equilibrium**

In practise, each individual is expected to selfishly minimize its bill. It can be shown that the selfish optimization is the same as the distributed implementation of the ECS optimization problem. Indeed, it is also the solution of the non-cooperative game naturally formed. [13] gives the details about the game but the intuition can be easily derived. The individual bill (5) is a share of the total bill across the whole network collaborative pool, that is, the solution of the optimization problem. Deviating from this solution can only increase the total bill and thus increase the individual bill as well.

## DISCUSSION AND PERSPECTIVES

A comparative assessment with different intermediate scenarios in the same context is available in [13]. Nonetheless, we can assure that in the considered context, the collaborative ECS is the best obtainable solution as it is the optimum solution that is computed.

An important subject of discussion concerns the hypotheses we assume when considering DSM. Today, most of the tariff schemes applied to Low Voltage consumers usually consist in a single or day and night prices. All the components of the bill (network cost, commodity cost, taxes…) are directly proportional to the energy index. The incentives for shaping the consumption to a more suitable pattern are very limited, if not inexistent. If policy makers wish an active participation of the consumers in the effort to a better consumption, the tariff structure should be redesigned. The smart grid can be truly smart only if the pricing is smart as well. Besides, they should associate the DSOs as one of the main facilitator for the implementation of active DSM scenarios. Indeed, through the rollout of Smart Meters and their efforts to modernize the networks, they contribute extensively to the transition to smarter grids.

Another interesting topic for this type of scenario would be the study of the flexibility consented by users depending on the hypotheses we choose for the DSM scenario. For instance, changing the cost distribution when billing the individuals can promote more or less flexibility. Despite a possible deviation from the global optimum, the selfish behavior expected of the individuals can incite them to be more flexible if they perceive an economic interest. The non-optimal cost in such case could be smaller than a scenario featuring an optimum cost but with less flexibility consented.

Finally, intraday schedule deviations should be tackled in order to further promote the ECS scenario that is presented.

## CONCLUSION

In this paper, we show that by sharing only the net individual scheduled loads to the other users of the network, a solution characterized by a Nash Equilibrium can be reached. The overall cost, reflecting both the real commodity and network costs, is optimum, and the consumers benefit from it in a fair manner without jeopardizing the other actors. Besides, the communication and computation can be conducted by Smart Meters, hence requiring no additional device or party. This DSM scenario, by involving each user in the objective through their cost impact, naturally leads to the adoption of more reasonable habits and the long-term promotion of cheaper and more renewable energy resources while considering the liberalized context adopted by many parts of the world.

## REFERENCES

[1] T. Jamasb, M. Pollitt, and M. Pollitt, “Electricity Market Reform in the European Union : Review of Progress toward Liberalization & Integration", *Design*, no. March, 2005.

[2] C. W. Gellings, “The concept of demand-side management for electric utilities,” *Proc. IEEE*, vol. 73, no. 10, pp. 1468–1470, 1985.

[3] P. Palensky, S. Member, D. Dietrich, and S. Member, “Demand Side Management : Demand Response , Intelligent Energy Systems , and Smart Loads,” vol. 7, no. 3, pp. 381–388, 2011.

[4] G. Strbac, “Demand side management: Benefits and challenges,” *Energy Policy*, vol. 36, no. 12, pp. 4419–4426, 2008.

[5] P. Siano, “Demand response and smart grids — A survey,” *Renew. Sustain. Energy Rev.*, vol. 30, pp. 461–478, 2014.

[6] A. J. Conejo, J. M. Morales, S. Member, L. Baringo, and S. Member, “Real-Time Demand Response Model,” vol. 1, no. 3, pp. 236–242, 2010.

[7] M. H. Albadi and E. F. El-Saadany, “A summary of demand response in electricity markets,” *Electr. Power Syst. Res.*, vol. 78, no. 11, pp. 1989–1996, 2008.

[8] S. Caron and G. Kesidis, “Incentive-Based Energy Consumption Scheduling Algorithms for the Smart Grid,” *2010 First IEEE Int. Conf. Smart Grid Commun.*, pp. 391–396, 2010.

[9] A. H. Mohsenian-Rad, V. W. S. Wong, J. Jatskevich, and R. Schober, “Optimal and

autonomous incentive-based energy consumption scheduling algorithm for smart grid," *Innov. Smart Grid Technol. Conf. ISGT 2010*, pp. 1–6, 2010.

[10] A. H. Mohsenian-Rad, V. W. S. Wong, J. Jatskevich, R. Schober, and A. Leon-Garcia, "Autonomous demand-side management based on game-theoretic energy consumption scheduling for the future smart grid," *IEEE Trans. Smart Grid*, vol. 1, no. 3, pp. 320–331, 2010.

[11] P. Samadi, A.-H. Mohsenian-Rad, R. Schober, V. W. S. Wong, and J. Jatskevich, "Optimal Real-Time Pricing Algorithm Based on Utility Maximization for Smart Grid," *2010 First IEEE Int. Conf. Smart Grid Commun.*, pp. 415–420, 2010.

[12] G. Hu and C. J. Spanos, "Distributed Energy Consumption Control via Real-Time Pricing Feedback in Smart Grid," pp. 1–8, 2014.

[13] M. Hupez, Z. De Grève, and F. Vallée, "Cooperative demand-side management scenario for the low-voltage network in liberalised electricity markets," *IET Generation, Transmission &* Distribution, vol. 12, no. 22, pp. 5990-5999, 2018.