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A Cooperative Demand-Side Management Scenario for the Low Voltage Network in Liberalised Electricity Markets

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Abstract: In the coming years, the energy sector is expected to significantly decrease its carbon footprint through the integration of more renewable energy resources. Adapting the demand-side to the changing reality of the supply-side is therefore essential. This work presents a cooperative Demand-Side Management scenario in a Low Voltage network considering a context of liberalised electricity markets. We show that introducing an additional inter-supplier cooperation mechanism among consumers enhances a better use of the flexibility consented by each individual, hence aiming at reaching a global optimum instead of optimising the costs of a few ones. To that end, a Real-Time Pricing scheme is explored based on cost functions differentiated both in time and consumption level that should reflect the true energy cost. We apply to each consumer a commodity cost function shared among the set of cooperative users of its respective supplier as well as one common network cost function shared by all cooperative users of all suppliers in the considered network. Each individual runs, through its Smart Meter, a decentralised optimisation algorithm defining an Energy Consumption Schedule for a set of flexible appliances. The mechanism we propose ensures that a fair cost distribution between all users is achieved by reaching the Nash equilibrium. To assess our proposition, we confront it to intermediate consumption strategies through a benchmark. The results confirm that our inter-supplier cooperation mechanism always leads to the minimum total cost.

Nomenclature

Functions and Variables

b_n	Daily billing amount charged to user n
$C_{q,DSO}$	Network cost function at quarter q
$C_{q,i}$	Cost function of supplier i at quarter q
L_q	Total network load at quarter q
$L_{q,i}$	Total load across all users of supplier i at quarter q
$x_{n,a}$	Energy consumption vector of appliance a for user n
$x^q_{n,a}$	Energy consumption of appliance a for user n at quarter q

Indices and Sets

χ_n	Energy consumption strategy set for user n
a, A_n	Index and set of electrical appliances of user n
i, S	Index and set of suppliers
n, N	Index and set of users in the network cooperative pool
N_i	Set of cooperative users for supplier i
q, Q	Index and set of the quarters of an hour

Parameters and Constants

$\delta_{n,a}$	Vector of permissible consumption time intervals of appliance a for user n
$\delta^q_{n,a}$	Consumption permissibility of appliance a for user n
Ω_n	Coefficient of bill distribution for user n
$a, b, c_{q,DSO}$	Network cost function parameters at quarter q
$b_{q,i}, c_{q,i}$	Commodity cost function parameters of supplier i at quarter q
d^q_n	Total non-shiftable load of user n at quarter q
$E_{n,a}$	Energy needs of appliance a for user n
$m_{n,a}, M_{n,a}$	Minimum and maximum power levels of appliance a for user n
N	Network cost associated to S_T
N^*	Network cost associated to S^*_T
n_s	The number of suppliers
S_i	Minimum possible commodity cost of the users of supplier i
S^*_i	Actual commodity cost
S_T	Total minimum possible commodity cost
S^*_T	Total actual commodity cost

1 Introduction

Climate change and environmental issues are leading the world into social, economic and political turmoil. They should be the primary concern of this 21st century, and humanity must look forward to solutions in order to limit their causes and consequences. The energy sector accounts for 35 % of greenhouse gases emissions [1], hence making it the biggest emitter due to the massive use of fossil energies. Furthermore, the large proportion of unburnable carbon [2] and the current distrust in nuclear energy limit the increase of capacities in the short term. Yet, the energy demand of emergent countries is expected to rise, and a substantial portion of the transportation and the space heating emissions could be possibly shifted to electricity generation, due to the growth of the electric vehicle (EV) pool and the increasing share of domestic heat pumps (HPs). There is therefore an urgent need for the energy sector actors to develop sustainable alternatives to help prevent a global disaster. Renewable energies, such as wind and sun, are promising candidates and their deployment is currently booming. This ramping shift of the generation mix introduces however many new challenges and issues. Among them, the intrinsic nature of wind and sun raises the problem of availability. The increasing share of renewables diminishes the flexibility on the generation side and leads to periods of higher total generation and others of lower global generation. The development of storage solutions is expected to answer partly to this issue, but another major option is to shift the flexibility on the users'side through Demand-Side Management (DSM) techniques.

DSM refers to all programs that aim at modifying consumer energy demand [3–5]. These can be classified under three main families. The Energy Efficiency programmes (EE) intend to reduce the energy needed by using more efficient products and appliances (e.g. improve house insulation, switch to LED lighting, install timers etc) [6] or by using conservation voltage reduction techniques [7]. Most of the efforts in the last 20 years have focused on these programmes using economic incentives and regulations. Load Management programmes (LM) anticipate the balance of the network by shifting loads appropriately. It aims at planning the use of the energy without imposing any hardship on the consumers. Finally, Demand Response programmes (DR) include responsive actions of power/energy reduction (peak shaving) through direct load control or voltage reduction and usually address operational issues [8–10]. Thereby, these three families of programmes address respectively long-term (days to years), medium-term (hours to days) and short-term actions (seconds to hours). LM and DR usually need one or more signal variables. If we assume that prices applied by the actors reflect the real cost of electricity all along the supply chain, they represent the most obvious variable to use. However, the true cost of electric energy is not constant with time. If the energy is to be used more rationally, consumers should be aware of it. Hence, different types of smart pricing exist and can be used as signals for the precited programs. Among the main smart pricing schemes, Time-of-Use pricing (ToUP) refers to electricity rates varying over one day and usually set well in advance for a prolonged period of time. It allows to capture daily patterns of generation and demand, hence suiting particularly the dynamics of a traditional generation mix characterised by its higher controllability. In a context of increased decentralised generation mix, the dynamics changes day after day and tariffing schemes such as Critical-Peak Pricing (CPP) or Real-Time Pricing (RTP) are better suited. The first aims at preventing heavy load conditions during critical periods of the day while the second reflects as closely as possible the current generation costs. Hence, RTP defines prices on a small-time interval basis (e.g. hour or quarter) usually communicated one day in advance [11–14]. These different types of dynamic pricings are enhanced by the on-going large-scale deployment of Smart Meters (SMs) units and the emergence of the smart grid concept in all Europe [15].

Besides, Europe has opted for the liberalisation of its energy markets at the turn of the millennium [16]. The underlying privatisations and splitting of integrated public companies have brought many new actors in the electricity markets. More actors and more rules have led to a much higher degree of complexity. Moreover, each party intends to reap the benefits to itself leading at times to divergent objectives. It can be witnessed that in many cases the focus is brought upon optimising benefits microscopically. Numerous timely solutions (e.g. microgrids, individual storage, ancillary services) aim too often at maximising revenues or minimising expenses of a few ones at the cost of the global welfare and the solution of the global equation. This reality is aggravated by the current context of gloomy perspectives for the western economy. Limited public investments are consented and private actors require quick return on investments, thus creating a growing gap between public and private interests.

While a DSM technique based on a global and centralised optimisation would be utopian and subject to other controversies (e.g. privacy, individual freedom), the introduction of cooperative mechanisms can enhance a more rational use of the energy. By modifying slightly individual objectives, it can be shown that the global cost of a system can be reduced, hence promoting renewable energy sources policies and strengthening social welfare. Energy Consumption Scheduling (ECS) is a type of LM in which flexible loads (e.g. dishwasher, electric vehicle, washing machine) are programmed in order to answer to an objective function [17, 18]. One approach uses this technique in a game theoretic framework using an autonomous and decentralised algorithm among users [19]. The players of the ECS game are the users of a utility company, and their respective strategies are the daily schedules of their household appliance. In that approach, the utility company applies Time-of-Use tariffs that differentiate the energy usage in time and level for the aggregated load. It shows that the obtained optimum in terms of minimising the energy cost is also the unique Nash equilibrium of the ECS game. Among the benefits, users can maintain their privacy as they do not need to reveal the details of their consumptions schedules to other parties, and furthermore, the peak-to-average (PAR) ratio and electricity charges are reduced.

In this paper, we take this cooperative mechanism even further and adapt it to the more complex reality of liberalised electricity markets. Indeed, most European countries and an increasing number of other countries have adopted a scheme in which electricity supply is ensured by different actors. Consumers can choose freely their energy supplier on a competitive market, but they are subject at the same time to transmission and distribution network costs associated to a fixed Transmission System Operator (TSO) and Distribution System Operator (DSO) in relation with their geographical location. The two main costs associated to electricity supply are thus the energy generation (commodity) costs and network use costs. Whereas it is easy to transpose the autonomous DSM programme of [19] to the commodity cost among the customers of a given electricity supplier, the current literature does not tackle the optimisation of both the network costs and the commodity costs under several suppliers. The network costs are indeed attributable to all its users without any distinction of electricity supplier, and its optimum usually does not match those of the energy suppliers. This highlights the need for an additional cooperation mechanism between all users of one network.

In this work, we focus on the day-ahead horizon. The objective is to schedule the energy consumption in an efficient way among consumers of a same cluster of feeders behind the same Medium Voltage (MV)/Low Voltage (LV) transformer. The use of a RTP is investigated to schedule energy consumption on a day-ahead basis. We assume RTP is used both by the electricity suppliers and the DSOs in order to reflect the reality more closely. Tariffs of transmission are not considered in this first version but the mechanism can be easily extended to the input of the TSOs. The contributions of this paper are summarised as follows:

- We present a cooperative mechanism between users of different electricity suppliers that minimises the sum of the costs associated to the common network utilisation and the energy generation by each supplier.
- We formulate the optimisation problem and show how it can be conveniently solved by all the participating consumers using a decentralised algorithm, hence ensuring more privacy.
- We propose a method for distributing the total costs fairly between the pools of the different electricity suppliers and billing accordingly their users inside each of these ensuring that the underlying ECS game between users has a unique Nash equilibrium.

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• We compare different levels of cooperation, from completely passive users to entirely cooperative users, in terms of costs and load profile.
• We study which are the most and least favourable circumstances for cooperation.

The next section contextualises the actors, their characteristics and their interactions giving the main hypotheses. Several scenarios considering progressive user behaviours and cooperation levels are detailed. The third section formulates mathematically the cost minimisation problem and details the algorithm of the ECS game. Some results of simulations are then exposed and discussed for the different considered scenarios in the fourth section. Finally, paper is concluded in section 5 along with some prospects.

2 Context and hypotheses

In this section, the different actors and their interactions as well as some generalities about the cost curves at stake are introduced. The proposed cooperation scheme along with other intermediate scenarios further used for comparison are presented.

2.1 *Actors and their roles*

2.1.1 End-users: They are the consumers connected at the nodes of the LV distribution network. They are thus mainly residential or small and medium businesses users. They present very heterogeneous profiles of consumption as they have, e.g. different hours of occupation, different devices, habits. Customers should retain free choice over their energy supplier and the will to cooperate or not. They are indeed inclined to more or less consumption flexibility according to the nature of their activity and general opinion of freedom. End-users comprise up to four different electric components:

• Non-shiftable consumption: this is the portion of the consumption on which users do not wish to consent any flexibility (e.g. lighting, fridge, TV, computer).
• Shiftable loads: these are devices for which time constraints are usually applicable but allow more or less flexibility for the load scheduling (e.g. dishwasher, EV, washing machine).
• Local generation: they are mainly the PV panels and represent a negative consumption without any flexibility.
• Storage: it can be seen as a shiftable load or generation (e.g. electric vehicle, battery pack).

In this work, the impact of storage is not considered. Storage will help improve the DSM strategy and we thus continue on-going work towards including such systems.

2.1.2 Distribution System Operators: DSOs are geographically circumscribed. They usually own large areas of MV and LV lines in a same region. They have a de facto monopoly and are consequently strongly regulated by states. End-users are thus bound to their geographical DSO. Although applicable tariffs are usually proportional to the total energy consumed and sometimes also to the peak power, it appears that they do not reflect the real cost of today's reality. Whereas in the past DSOs sought only to maintain and renew their infrastructure on a time basis with little or no effect of the consumption variations, the more stringent operating conditions of the network introduced by decentralised generation lead to operational issues such as voltage range infringements or backflowing. An active management of the network mostly depending on power flows will be a major point of focus in the short term. It is clear that the cost for DSOs is optimised when its load is most uniform throughout the day hence keeping the PAR as low as possible. DSOs and regulators should therefore develop a new tariff structure reflecting that reality. Paragraph 2.1.4 develops this consideration further.

2.1.3 Electricity Suppliers: In the context of liberalised electricity markets, numerous suppliers can offer electricity to the users.

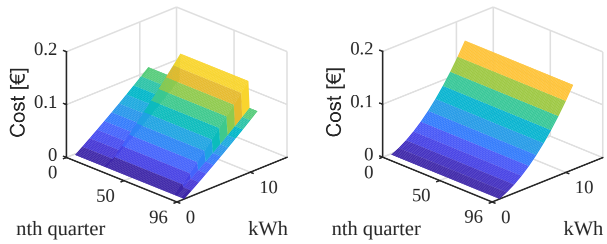


Fig. 1: Example of a supplier cost curve (left) and a DSO cost curve (right).

Suppliers usually have different selling strategies depending on the different generation portfolio they hold and their market positioning. In the effort to consume energy more efficiently, dynamic pricing could become widespread as explained earlier. The popular day and night rates are a simplistic application of ToUP. However, due to the high variability of renewables, prices should be much more granular. Besides, in order to increase the penetration of renewables in a healthy manner, it is to the utmost importance that suppliers offer transparent tariffs reflecting closely the energy mix, its dynamics and the variations due to forecasts and market prices. Customers can hence choose the right supplier with the right price dynamics suiting its needs at the lowest cost and thus helping at consuming energy more rationally.

2.1.4 Cost curves: In this work, we assume that cost curves [€] are defined by each actor on a day-ahead basis. They comprise one cost function for each interval of the day considered. In this work, we choose 15 minutes time intervals as many SMs have adopted that specific resolution [20]. Instead of having one constant price [€/kWh] leading to a passive attitude of end-users, applying a higher granularity and a possible progressiveness in function of their consumed energy can help shape the desired behaviour and implement DSM scenarios. However, it is important that the curve shape reflects the reality of underlying costs.

We consider for the network contribution a pricing scheme differentiated both in time and level of consumption (cf. Fig. 1 right). Indeed, DSOs do not have any degree of flexibility and they should reflect the utilisation burden as it is. The consequences of power flowing in the network remain the same throughout time (some exogenous factors such as MV considerations could still motivate DSOs to differentiate the cost curves through time as well), however, they are enhanced depending on the level of solicitations. Indeed, charges such as power losses or the wear and tear of assets increase superlinearly, e.g. cable ohmic losses increase with the square of the current. Hence, we define a cost curve, constant in time and increasing quadratically with the consumption, i.e. prices increasing linearly (cf. 3.1.2). This last assumption is a sweeping simplification of the real network costs.

On the other hand, energy suppliers have access to some flexibility. Depending on their portfolio content (generation assets, market participations), the energy mix is characterised by different time-dependent costs. However, we choose not to differentiate the prices in function of their level of consumption, i.e. linear costs, as suppliers have some degree of freedom and useful tools at their disposal, and for the sake of simplicity towards consumers (cf. Fig. 1 left). Indeed, they should be able to easily select the offer that suits their needs best. The higher complexity that those curves can hold should be carefully governed by a few simple indicators that makes it possible to easily compare different contract offers. Among those, some could be:

• Mean price,
• Minimum/maximum prices,
• An indicator of the variability between the different time intervals (degree of flexibility required) etc.

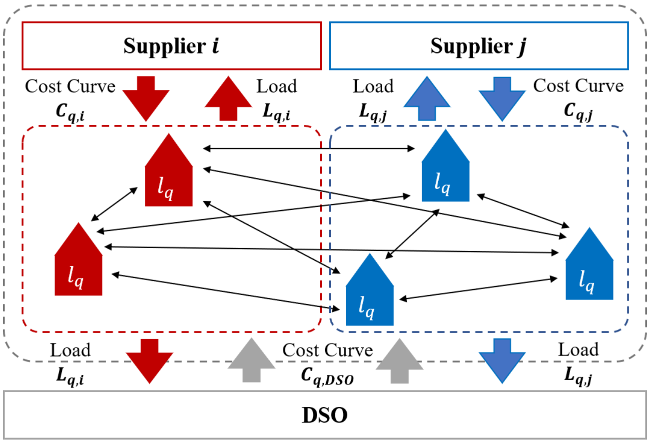


Fig. 2: Interactions between the different actors of the inter-supplier ECS scenario.

TSO curves are not considered in this work, however, a possible option is the generalisation of DSO curves.

2.2 *Scenarios of Cooperation*

As the main contribution of this paper, we propose to use the ECS capability introduced by the SM so as to set up a cooperation mechanism between users of different suppliers on a same LV network to decrease the total energy cost. In order to assess the proposition, it is convenient to benchmark some results with different intermediate situations. Hence, we choose to review different scenarios that include progressive cooperation and proactivity on the user's side. The different scenarios considered are the following:

- Passive demand: the users take absolutely no reactive actions towards the price signal. Despite the varying prices, they act as if they were subject to constant fares: they consume energy starting at the beginning of the respective possible time intervals of each device.
- Flattened demand: the users modulate their appliances in such a manner that they consume a constant power during the whole respective possible time intervals attributed, thus guaranteeing a low PAR.
- Intra-supplier ECS: the users of a given cooperative supplier pool schedule their load together in order to minimise the commodity cost.
- Inter-supplier ECS: the users of all cooperative supplier pools (the DSO cooperative pool) schedule their load in order to minimise both commodity and network costs. This is the main contribution of this paper.

Passive demand and flattened demand are respectively a pessimistic and an optimistic scenario when no ECS is considered. They are both unrealistic but they can be seen as upper and lower bounds of what could be some realistic consumption schemes.

2.3 *Communication and interactions*

In this paragraph, we focus only on the scenario of inter-supplier ECS. Indeed, passive and flattened demand do not require any sort of interaction between actors while the intra-supplier ECS can be considered as a special case of inter-supplier ECS, when only one actor playing the role of both supplier and DSO is imposed to all consumers.

Hence, all cooperating users exchange their individual aggregated load through their Smart Meter (cf. Fig. 2). That information is only necessary for the Energy Consumption Scheduling algorithm and it is therefore not stored (cf. 3.4). In addition, each supplier sends the price information to each of its customers. In return, the aggregated load of each supplier pool is communicated to their respective supplier for billing. All the aggregated loads of the network are made available to the DSO and the network cost curve is applied to everyone. In this manner, no individual load is stored hence maintaining privacy. The next section formalises mathematically each of these interactions.

3 Methodology

The mathematical models and formulations of the different scenarios of cooperation are exposed in this section. The intra-supplier ECS scenario is somewhat similar to the problem of [19] with the difference that we apply distinct network costs in the current context. Furthermore, we choose to add the contribution of the non-shiftable components in the cost functions. But it is the inter-supplier ECS scheme that holds the main novelty of this paper, and therefore, we further emphasise the related ECS game and its algorithm.

3.1 *Analytical Models*

3.1.1 Power Network: Let us consider a LV distribution network such as discussed in section 2 of which all users take part in the cooperative pool of their supplier and their DSO. These should have ECS capability and a SM with means of communication between users (cf. 2.3). We assume that n_s different suppliers are available. N denotes the set of users in the network cooperative pool and N_i addresses the set of cooperative users for supplier i. Hence, $i \in S\{1, \ldots, n_s\}$. Without loss of generality, a time resolution of one quarter of an hour is considered as it is a common time resolution adopted for SM [20]. Hence, the total load across all customers of supplier i at each quarter of the day $q \in Q \triangleq \{1, \ldots, 96\}$ is denoted $L_{q,i}$ and the total network load $L_q = \sum_{i=1}^{n_s} L_{q,i}$.

3.1.2 Electricity Cost Models: For each quarter of an hour, we define for each supplier a cost function $C_{q,i}$ for the commodity as well as one common cost function attributable to distribution costs $C_{q,DSO}$. As previously explained in section 2, we choose to assume respectively quadratic cost functions and linear cost functions. Hence, they follow:

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

$$C_{q,DSO}(L_q) = a_{q,DSO}L_q^2 + b_{q,DSO}L_q + c_{q,DSO} \tag{2}$$

where $a_{q,DSO} > 0$ and $b_{q,i}, b_{q,DSO}, c_{q,i}, c_{q,DSO} \geq 0$ at each quarter of an hour $q \in Q$. It should be noted that cost functions can hold any structure that makes the resultant cost surface convex (cf. 3.2.2).

3.1.3 Low Voltage Load Model: For each user $n \in N$, we define both the shiftable and the non-shiftable loads. Non-shiftable load is defined as the difference between the consumption for which no flexibility can be reasonably agreed (e.g. lighting, fridge, cooking stove) and the potential PV generation. The total non-shiftable load for user n at quarter q is denoted by:

$$d_n^q \triangleq [d_n^1, \ldots, d_n^{96}] \tag{3}$$

In contrast, the shiftable consumption of one individual includes devices such as washing machines, dishwashers, EVs, for which the operation can be scheduled with more or less constraints. This set of electrical appliances for user n is denoted by A_n and each appliance $a \in A_n$ is described by a consumption scheduling vector:

$$x_{n,a} \triangleq [x_{n,a}^1, \ldots, x_{n,a}^{96}], \tag{4}$$

where $x_{n,a}^q$ corresponds to the shiftable consumption vector of appliance a for user n at quarter q. The quarterly load for each user

n is therefore calculated as:

$$\sum_{a \in A_n} x_{n,a}^q + d_n^q = l_n^q \tag{5}$$

Based on these definitions, the total load across all users of supplier i cooperative pool is:

$$\sum_{n \in N_i} l_n^q = L_{q,i} \tag{6}$$

Each appliance for each consumer requires a predetermined amount of energy over one period of 96 quarters, we denote it by $E_{n,a}$. Furthermore, some time constraints are generally applicable. For instance, an EV should be reasonably charged when the owner needs to use it. Let

$$\delta_{n,a} \triangleq [\delta_{n,a}^q \in \{0,1\}; q = 1, \ldots, 96], \tag{7}$$

a binary vector, describe the permissible time intervals of consumption for a specific appliance (1: permitted; 0: not permitted). Hence, the total scheduled load for one device during permissible quarters equals the predetermined energy consumption and is null for all non-permissible quarters. That is,

$$\delta_{n,a}.{x_{n,a}}^T = E_{n,a} \tag{8}$$

and

$$not(\delta_{n,a}).{x_{n,a}}^T = 0. \tag{9}$$

Finally, all devices are subject to technical constraints. Each device has its own consumption profile. However, in this work, we choose to simplify the problem and define only minimum and maximum power levels, hence allowing a complete modulation of the consumption. It is assumed that:

$$m_{n,a} \leq 4.x_{n,a}^q \leq M_{n,a}, \quad \forall q \in Q \tag{10}$$

All the possible consumption scheduling vector for any user n can be summarised by:

$$\chi_n = \Big\{ x_n | \delta_{n,a}.{x_{n,a}}^T = E_{n,a}, not(\delta_{n,a}).{x_{n,a}}^T = 0, \\ m_{n,a} \leq 4.x_{n,a}^q \leq M_{n,a}, \quad \forall q \in Q \Big\} \tag{11}$$

with x_n being the aggregation of all appliances' scheduling vectors $x_{n,a}$.

3.2 Problem Formulations

3.2.1 Non-Optimised Strategies: Passive and flattened demand are simplistic and unrealistic scenarios for which it is assumed that:

• Passive demand users schedule their load as if each appliance would consume at its maximum power $M_{n,a}$ from the beginning of the respective permissible time intervals until the total energy needed $E_{n,a}$ is consumed. The additional constraint to (11) is therefore:

$$x_{n,a}^q = M_{n,a} \quad \forall q : \sum_{k=1}^{q} \delta_{n,a}^k \leq \frac{4.E_{n,a}}{M_{n,a}} \tag{12}$$

• Flattened demand consumers are aware that high level of power consumption is detrimental to the network and can be most prejudicial in terms of costs. In an effort to avoid a high PAR without requiring any optimisation capability, they can judiciously modulate the consumption of each appliance so that they consume a constant power over the whole permissible time scheduling intervals. That is, the extra constraint:

$$\delta_{n,a}^q.x_{n,a}^q = \frac{E_{n,a}}{\sum_{q=1}^{96} \delta_{n,a}^q} \delta_{n,a}^q \quad \forall q \in Q \tag{13}$$

3.2.2 Energy Consumption Scheduling Strategies: Although the scheduling optimisation can aim at solving technical considerations such as the minimisation of the PAR, we focus on minimising energy costs. The intra-supplier ECS minimises costs attributable solely to the energy generation while the inter-supplier ECS minimises the total energy cost including distribution costs for all cooperative users. As previously discussed, we assume that energy cost functions are carefully designed to reflect the true cost.

• In the intra-supplier ECS scheme, each supplier i minimises the following function:

$$\min_{x_n \in \chi_n, \forall n \in N_i} \sum_{q=1}^{96} \sum_{n \in N_i} C_{q,i} \left(\sum_{a \in A_n} x_{n,a}^q + d_n^q \right) \\ \text{s.t. constraints} \quad (8), (9), (10) \tag{14}$$

Problem (14) is linear and may have more than one optimal solution achieving the same minimum total cost. We consistently choose the solution leading to the flattest power consumption cycle for each device in an effort to limit the underlying network costs. The problem can be solved using a linear programming method such as the simplex algorithm or the Interior Point Method (IPM).
• In the inter-supplier ECS strategy, the optimisation problem integrates the network cost component and is expressed by the following expression:

$$\min_{x_n \in \chi_n, \forall n \in N_i, \forall i \in S} \sum_{q=1}^{96} \sum_{n \in N_i} \left[\sum_{i=1}^{n_s} C_{q,i} \left(\sum_{a \in A_n} x_{n,a}^q + d_n^q \right) \right. \\ \left. + C_{q,DSO} \left(\sum_{a \in A_n} x_{n,a}^q + d_n^q \right) \right] \text{ s.t.} \quad (8), (9), (10) \tag{15}$$

The IPM technique among other convex programming methods can be used to solve problem (15) as well. The solution of problem (15) is unique given the strict convexity of the resulting cost function.

We can also rewrite (14) and (15) as:

$$\min_{x_n \in \chi_n, \forall n \in N_i, \forall i \in S} \sum_{q=1}^{96} C_{q,i} \left(L_{q,i} \right) \tag{16}$$

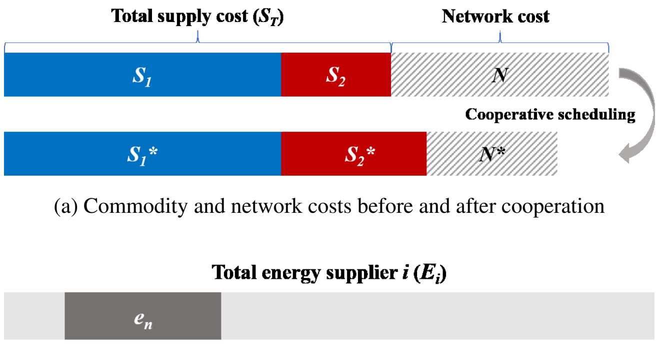
and

$$\min_{x_n \in \chi_n, \forall n \in N_i, \forall i \in S} \sum_{q=1}^{96} \left[\sum_{i=1}^{n_s} C_{q,i} \left(L_{q,i} \right) + C_{q,DSO} \left(L_q \right) \right] \tag{17}$$

respectively. Instead of solving the optimisation problems in a centralised fashion, it is interesting to take advantage of the ECS capability of the SM. Indeed, this functionality allows a distributed resolution with a minimum exchange of information between SM.

3.3 Energy Consumption Game

Both ECS optimisation problems naturally form a game for which a Nash equilibrium exists under a few assumptions. However, in the intra-supplier scenario, only the commodity cost component forms such a game. Indeed, there is no cooperation between users of different suppliers on the network cost component and thus the exchange of information is limited to the SM of a same supplier pool. The formulation in this case is similar to [19] where only the commodity



(a) Commodity and network costs before and after cooperation

(b) Fraction of consumed energy by user n

Fig. 3: The costs are distributed according to the initial commodity costs ratios (a) and the fraction of energy consumed inside a given supplier (b).

cost would be considered. We focus on the inter-supplier scenario game for which the cooperation mechanism proposed in this paper is introduced.

3.3.1 Users'billing: Let's define the components of the total bill:

- S_i: minimum possible commodity cost of the users of supplier i (solution of the intra-supplier ECS), cf. (18)
- S_T: total minimum possible commodity cost, cf. (20)
- N: network cost associated to S_T
- S_i^*: actual commodity cost
- S_T^*: total actual commodity cost
- N^*: network cost associated to S_T^*

with

$$\begin{cases} S_i = \min\limits_{x_n \in \chi_n, \forall n \in N_i} \sum\limits_{q=1}^{96} C_{q,i}(L_{q,i}) & (18) \\ S_T = \min\limits_{x_n \in \chi_n, \forall n \in N} \sum\limits_{i=1}^{n_s} \sum\limits_{q=1}^{96} C_{q,i}(L_{q,i}) & (19) \\ S_T^* + N^* = \sum\limits_{q=1}^{96} \left[\sum\limits_{i=1}^{n_s} C_{q,i}\left(L_{q,i}\right) + C_{q,DSO}\left(L_q\right) \right] & (20) \end{cases}$$

Issuing the individual bills of inter-supplier cooperative users is not straightforward. Indeed, reaching the total minimum cost requires for the users of each supplier pool to deviate from the optimal solutions S_i in terms of commodity cost (cf. Fig. 3a). Some suppliers will deviate more or less from what would be their respective optimum (S_i to S_i^*) in order to decrease the network costs (N to N^*) and the subsequent total cost across all cooperative users. This leads to a higher total commodity cost $S_T \leq S_T^*$. More importantly it creates a distortion in the relative contribution of each supplier to the total cost when $S_i^*/S_j^* \neq S_i/S_j$. Passing on the respective costs of each supplier after optimisation as it is would be inequitable. Hence, in order to apply a fair individual billing, we propose a twofold distribution of the total cost:

- 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, i.e. first fraction of (21). This corresponds to the optimal solutions of the respective intra-supplier ECS.
- Distribution between the users of each supplier proportionally to their fraction of total daily consumption in their respective supplier pool (cf. Fig. 3b), i.e. second fraction of (21).

Let's denote by b_n, the daily billing amount charged for each user $n \in N$ at the end of one day for both the network costs and commodity costs:

$$b_n = \frac{S_i}{S_T} \frac{e_n}{E_i} (S_T^* + N^*), \quad \forall n \in N_i \tag{21}$$

We can rewrite (21) as:

$$b_n = \Omega_n (S_T^* + N^*) \tag{22}$$

with

$$\Omega_n \triangleq \frac{S_i}{S_T} \frac{e_n}{E_i} \tag{23}$$

The billing system introduces a distribution between users naturally leading to a game with a unique Nash equilibrium as further described in the following paragraph. Furthermore, we see from (18)-(20), (21) that the DSO and the suppliers only need respectively $L_{q,DSO}$ and their corresponding $L_{q,i}$ for billing purposes. As previously introduced (cf. 2.3), no individual load information is thus communicated apart from a total consumption index (e_n).

3.3.2 Game Model: The underlying ECS game formed by the users in the intra-supplier scheme is expressed as follows:

- Players: all N users in the cooperative DSO pool.
- Strategies: they are the possible energy consumption schedules x_n that each user can set.
- Payoffs:

$$P_n(x_n; x_{-n}) = -b_n = -\Omega_n (S_T^* + N^*) \tag{24}$$

with $x_{-n} \triangleq [x_1, \ldots, x_{n-1}, x_{n+1}, , x_N]$, the vector containing all the users other than user n.

Given the strict convexity of all resulting cost functions at each quarter, the Nash equilibrium of the game always exists and is unique [19, Th. 1]. Furthermore, this unique Nash equilibrium is the optimal solution of the energy cost minimisation problem [19, Th. 2].

3.4 Distributed Algorithm

The global optimal solution of the energy cost minimisation problem can be achieved concurrently with reaching the unique Nash equilibrium by implementing an adaptation of the decentralised algorithm proposed in [19]. The cost functions differ in their structure made up of two contributions, but the resulting expressions keep the same properties.

$$\min_{x_n \in \chi_n, n \in N_i} \sum_{q=1}^{96} \Bigg[C_{q,DSO} \left(\sum_{a \in A_n} x_{n,a}^q + d_n^q + \sum_{m \in N \setminus \{n\}} l_m^q \right) + C_{q,i} \left(\sum_{a \in A_n} x_{n,a}^q + d_n^q \right) + \sum_{j=1}^{n_s} C_{q,j} \left(\sum_{m \in N_j \setminus \{n\}} l_m^q \right) \Bigg] \tag{25}$$

Hence, each user solves iteratively a local problem (25) using IPM before broadcasting the updated solution. We note that only the aggregated energy consumption vector $l_{m,q}$ is exchanged between the Smart Meters of the cooperating users but it does not need to be stored and made available to any party (cf. 2.3). The convergence and optimality of this algorithm are demonstrated in [19, Th. 3]. One great advantage that can be highlighted is the strategy-proof property of the algorithm. Indeed, as the users are charged proportionally to the total energy cost, deviating from the optimum by cheating would involve a higher bill for anyone. This consideration is highlighted with more details in [19, Th. 4].

Table 1 Load specifications of the study-case

Load Types	# in feeder	Max Power ($M_{n,a}$) [kW]	Energy needs ($E_{n,a}$) [kWh]	Energy Proportion
SLPs	15	NA	6	28.5%
EVs	7	4	6	13.3%
FAs	30	1	1	9.5%
HPs	11	1.6	14	48.7%

4 Benchmark

4.1 Case study and Load Specifications

The case study is built on a projection of what could be a residential feeder around the year 2030 in Belgium when technology and policies should be mature enough for enhancing such DSM strategies. On the one hand, current characteristics of the electric load are retained but on the other hand, new likely perspectives for domestic electricity demand are incorporated. Hence, the expected electrification of the transportation sector through EVs and hybrid vehicles and the electrification of the building heating systems through electric HPs are considered. These radical changes are expected to increase the share of flexible loads. We choose to emphasise what could be a modern LV network feeding a new neighborhood. The average annual electricity consumption per household in Belgium (Brussels [21]) is estimated at around 3000 kWh when considering no electric heating systems and cooking using gas. Among domestic appliances, it is reasonable to consider that some flexibility could be consented by dishwashers, washing machines and dryers, i.e. Flexible Appliances (FAs). These account for about 25 % of the load. Besides, there are strong commitments of governments to reach ambitious targets in terms of EVs penetration and major manufacturers consider the electric option for all their models in the medium term (e.g. Volvo in 2019, Volkswagen in 2030). The EV30/30 IEA plan, already adopted by countries such as France, Germany, the Netherlands, the USA or the UK foresee a share of EVs of 30 % by 2030 [22]. Moreover, electric HPs installation grows exponentially. It is expected to provide about 20 % of the household heating by 2030 and 65-75 % of new houses as soon as 2020 in the Netherlands [23]. Considering that households in Belgium own on average 1.5 cars [24], [25], and the growing success of HPs, both presenting strong flexibility potential, we choose to incorporate these two perspectives in our case study. Hence, based on these considerations, we assume the following mean individual load characteristics for the case study:

- 6 kWh of non-flexible load (e.g. lighting, TV, computer, oven): a same standardised Synthetic Load Profile (SLP) is considered for each user. In future works, forecasts could be considered.
- 2 kWh of FAs (e.g. dishwasher, washing machine, dryer): users are attributed a certain number of 1 kWh loads with a maximum power of 1 kW.
- 3 kWh for EVs (average of 50 km/day with 1.35 kWh/10 km, 1.5 cars/household and 30 % penetration).
- 10.25 kWh for HPs (average of 5000 kWh/yr and 75 % penetration).

We choose to assess our energy consumption scenarios on a LV feeder of $N = 15$ users with different energy needs and constraints. In each simulation, we attributed a random combination of the different load types presented in Table 1 and their possible scheduling possibilities ($\delta_{n,a}$). The constraints consider some reasonable habits such as the fact that most cars are home and available for charging at night. Besides, the users are randomly attributed to 4 different energy suppliers applying different quarterly pricing schemes. The input data are available for reproduction (contact author).

4.2 Results

Table 2 summarises the results for 100 simulations. The comparison of the results obtained for the 4 different consumption strategies shows that the inter-supplier ECS scheme achieves the best results as expected. Indeed, it is the only strategy that minimises the total cost. Although there is a substantial decrease between passive and flattened demand strategies (PD and FD), it should be noted that the passive demand strategy is a worst-case scenario as it schedules devices with permissible time slots in the first hours of the morning all at once. In reality, it is more likely that a passive consumption behavior would lead to a somewhat more distributed schedule and thus to a situation between the passive demand and flattened demand strategies. The flattened demand strategy can be considered as an elementary LM strategy. Indeed, it requires some control capability in order to modulate the power consumption. However, this strategy, though oriented towards decreasing network costs, does not address the commodity costs. On the contrary, intra-supplier ECS seeks the minimisation of the latter costs. Nevertheless Table 2 shows that cooperating only on commodity costs fails to decrease the total costs significantly. It even turns out to be less advantageous than the flattened demand strategy in 25 % of the simulations. Indeed, as expected the commodity contribution is greatly decreased but the network contribution neutralises the cost reduction. Hence, only a strategy involving a cooperation mechanism between all the users proves to be relevant. Furthermore, it does not require any additional communication as only the aggregated consumption of each user is communicated using the SMs.

Table 2 Results of the simulations in terms of costs

Costs [€]	Commodity	Network	Mean Total
Passive demand	42.21	80.16	122.38
Flattened demand	42.12	47.80	89.92
Intra-supplier ECS	36.20	53.06	89.26
Inter-supplier ECS	37.14	47.95	85.09
TC reduction [%]	**PD to FD**	**FD to Intra**	**FD to Inter**
Mean	26.5	0.7	5.4
Minimum	23.7	-4.6	3.8
Maximum	30.2	3.4	6.6

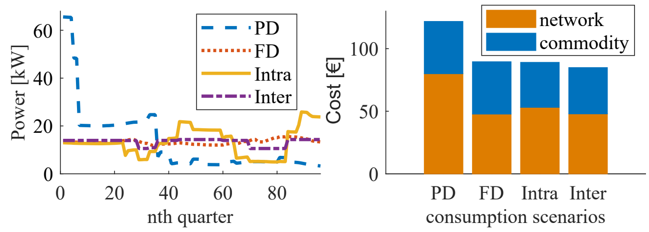


Fig. 4: Total power of the feeder when considering the different strategies (left) and their underlying costs (right) for one simulation example.

The impact of the different strategies on the aggregated power curves is depicted on Fig. 4 through one simulation example. It shows, as previously mentioned, that the passive users have most of their consumption taking place at the beginning of the day leading to high related network costs and non-optimal commodity prices. As expected, the flattened demand leads to a curve that is much flatter as all devices except the non-flexible loads consume a constant power over their permissible range of time. The network costs are hence significantly decreased. The intra-supplier ECS has a quite variable power curve as each user tries to exploit the cheaper time slots of their related supplier. In contrast, the inter-supplier ECS tempers the variability of the power curve in order to limit the increase in network costs.

Despite the effort of shaping what could be future realistic conditions, the numbers obtained are dependent on the conditions we have imposed. However, the main conclusions remain unchanged as long as the main hypotheses apply, that is, reflecting as closely as possible the true costs to each actor of a liberalised electricity market by using appropriate cost functions. Whereas one individual, through the power generation it requires, affects only the other customers of

Table 3 Results of the simulations in terms of costs; 47 % PV penetration

Mean costs [€]	Commodity	Network	Mean Total
Passive demand	27.88	87.38	115.25
Flattened demand	27.85	36.74	64.58
Intra-supplier ECS	21.96	35.86	57.82
Inter-supplier ECS	23.28	23.48	46.76
TC reduction [%]	**PD to FD**	**FD to Intra**	**FD to Inter**
Mean	43.9	10.4	27.6
Minimum	42.1	-9.7	24.7
Maximum	45.8	21.3	30.3

Table 4 Results of the simulations in terms of costs; 100 % PV penetration

Mean costs [€]	Commodity	Network	Mean Total
Passive demand	11.83	131.44	143.27
Flattened demand	11.69	65.76	77.45
Intra-supplier ECS	5.71	58.97	64.68
Inter-supplier ECS	12.07	13.74	25.81
TC reduction [%]	**PD to FD**	**FD to Intra**	**FD to Inter**
Mean	45.9	16.3	66.7
Minimum	43.2	-17.1	63.6
Maximum	48.0	41.4	69.3

its supplier, it also influences every other user on a same network through its underlying power flows. Hence, only a strategy considering a global approach can lead to an optimised schedule in terms of global costs. In that regard, the introduction of cooperation mechanisms proves to be a judicious solution as it requires no services of a third party and no additional piece of equipment.

4.3 Impact of Photovoltaic Generation

In the previous section, it is shown that the inter-supplier cooperation mechanism leads to the optimal total cost solution. Despite the numerous parameters at stake, the decrease in the total bill can be considered as substantial. We show that this is further accentuated when we introduce some PV generation.

Introducing solar panels in our simulations is highly relevant. Today already, some substantial amount of solar power is deployed and even though the increase in share of this technology is difficult to predict due to policy uncertainties, it is clear that the technical advances and the price decreases should promote a steady growth of new installations in the future.

Hence, we simulate the different strategies with the same feeder described in 4.1 under different PV penetration rates (20 %, 47 %, 67 % and 100 %). One day of clear sky is reproduced with solar facilities delivering 2.88 kW each at the maximum of the day.

The results discussed in 4.2 remain valid but are even more acute. Indeed, the inter-supplier ECS reduce the total costs drastically (cf. Table 3 and Table 4 for 47 and 100 % penetration rate and Appendix 5 for the rest). On the other hand, a poorly effective consumption strategy such as the passive demand or flattened demand can lead to higher total costs at the higher penetration rates while a significant portion of the energy is provided by the sun for free. This paradoxical situation is easily explained by the fact that the network can be highly loaded if the network pool auto-consumption level is low, hence leading to high network costs. Optimising only on commodity costs through the intra-supplier ECS can lead at times (14 and 5 % of the cases under 70 and 100 % penetration rate respectively) to higher prices than flattened demand for the same reasons. Indeed, it tends to favour selling the energy (we assume the same pricing scheme applied by the suppliers), thus decreasing commodity costs, but leads to high PAR on the network. These considerations are reflected in the shapes of the total power of the feeder and the different underlying costs obtained for one example of simulation, cf. Figure 5.

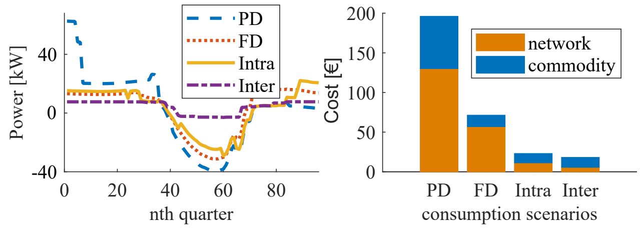


Fig. 5: Total power of the feeder when considering the different strategies (left) and their underlying costs (right) for one simulation example with 100 % PV penetration rate.

Introducing PV in the inter-supplier ECS scenario does not affect the distribution of the costs and the Nash equilibrium. Indeed, the expressions previously introduced remain unchanged. The distribution is fixed according to the ratio when optimisation is completed only on commodity costs. Only, e_n and E_i are respectively the individual energy and total energy of supplier i consumed and withdrawn from the electric network. The energy produced and consumed in situ by an individual are therefore not accounted for. Henceforth, PV facilities provide free energy for its owner when available and the surplus allows to decrease its supplier cooperative pool bill. Some further distribution mechanisms could be examined, for instance, a retribution of the owner for their surplus at the price of the supplier. The recipient would still benefit from this distribution because of the decreased underlying network costs.

5 Conclusion

This paper presents a solution for an optimised day ahead scheduling of LV consumers on a same network in terms of global costs, i.e. commodity costs and network costs. This was presented in detail starting with a description of the context and different scenarios of energy consumption strategies. Then, the methodology adopted for the different strategies was described with an emphasis on the inter-supplier ECS. Finally, a benchmark conducted on 15 users of a same LV network was studied. Results have confirmed that in a realistic scenario for 2030, the inter-supplier cooperation strategy introduces in average more than 5 % of additional savings on the total cost in comparison with different DSM strategies without the cooperation mechanism. The savings are much more pronounced with the introduction of PV as an efficient management of network flows is essential. The optimised solution reached by the inter-supplier ECS and its inherent Nash equilibrium in the cost distribution among users proves to be a promising option to be developed for a smarter electricity consumption.

Global costs should be the main point of focus of policy makers as they reflect the cost for the society as a whole. LM programs seek to use the difference of consumption needs between users in order to better use the flexibility consented by each of them and hence leading to diminished global costs. For such strategies to be applied, consumers should all be aware of the actual costs they pose. The consumption information must therefore be shared, and costs determined together beforehand. The users that do not wish to participate in this effort can only be subject to either predetermined prices that do not reflect the true cost (current situation) or account their underlying cost contribution afterwards with all the inherent disadvantages. In order to implement a DSM scenario for the LV network in a liberalised electricity market, it is essential to share the needs of all the users forming a same price contribution. In this paper, they are all the users behind a same MV/LV transformer which are subject to a same network cost curve. Indeed, each user modifies the price for all the other users. Consumption needs can be either centralised by a third party responsible for determining each user's schedule or be shared among all users fostering the cooperation mechanism even further. The latter solution, which we chose in this work, has the advantage to require only a few lines of codes in the SMs and no additional resources. The decentralised algorithm solves the optimisation problem while keeping privacy.

Intraday modifications of the schedule and events requiring short time reactions as well as the errors on the forecasted non-shiftable load introduce deviations from the initial solution. Studying the numerous impacts of these deviations and suggesting a solution for handling all these considerations could be essential. Also, addressing the effects of the growing introduction of storage solutions enhanced by cheaper domestic storage and the batteries of the EVs should be a priority. In addition, developing solutions handling uncertainty issues due to the non-shiftable load are an important prospect as well. This is even more accentuated by the introduction of solar panels which have a strong stochastic behavior. Finally, studying alternative distributions of the surplus value between the participants through other pay-off functions or cooperative game setups could enhance new possibilities such as encouraging more flexible behaviours.

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Table 5 Results of the simulations in terms of costs; 20 % PV penetration

Mean costs [€]	Commodity	Network	Mean Total
Passive demand	36.28	78.24	114.52
Flattened demand	36.07	38.49	74.56
Intra-supplier ECS	30.11	41.60	71.71
Inter-supplier ECS	30.74	36.40	67.14
TC reduction [%]	**PD to FD**	**FD to Intra**	**FD to Inter**
Mean	34.9	3.8	9.9
Minimum	31.8	-6.4	7.2
Maximum	37.6	8.0	11.5

Table 6 Results of the simulations in terms of costs; 67 % PV penetration

Mean costs [€]	Commodity	Network	Mean Total
Passive demand	21.95	100.13	122.08
Flattened demand	21.83	43.44	65.27
Intra-supplier ECS	15.87	39.81	55.67
Inter-supplier ECS	17.98	16.05	34.03
TC reduction [%]	**PD to FD**	**FD to Intra**	**FD to Inter**
Mean	46.5	14.6	47.9
Minimum	44.4	-16.5	45.1
Maximum	48.7	31.4	49.9

Appendix

Table 5 and 6 summarise the results obtained for the simulations conducted according to the conditions specified in 4.1 with 20 and 67 % of the users producing electricity with solar panels. The observations are discussed in 4.3.