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A Three-Stage Strategy with Settlement for an Energy Community Management Under Grid Constraints

Muhammad A. Putratama, Rémy Rigo-Mariani, Alyssa D. Mustika, Vincent Debusschere, *Senior Member, IEEE*, Amaury Pachurka, and Yvon Bésanger, *Senior Member, IEEE*

Abstract—This paper focuses on a local energy market where a group of households in a low voltage (LV) grid is organized as an *energy community*. A three-stage management strategy is proposed under the French *collective self-consumption* framework. In the first day-ahead stage, households coordinate with the community manager to minimize the overall energy bills for the next day. Then, real-time operation (second stage) focuses on the mitigation of forecast uncertainties and voltage violation, by utilizing the reserve of the local production/storage assets. Finally, the third stage contractually allocates the community energy among the households on 30 min basis (based on the French regulation), in order to ensure fair individual cost reduction and possibly create economic surplus in the community. The proposed community management strategy is evaluated on a LV grid with 55 households, and the results show the proposed strategy achieve an average of 30 % individual cost reduction among the users compared to the base scenarios. Furthermore, different pricing scenarios are compared through sensitivity studies and scalability tests are run on larger systems.

Index Terms—Energy community, local energy market, energy management system, optimal power flow, distributed voltage control.

I. INTRODUCTION

THE growth of distributed energy resources (DERs) such as photovoltaic (PV) and energy storage systems (ESS) in residential-level has been increasing rapidly over the past years [1]. These phenomena incur change in end-users' behavior, moving from traditional consumers to *prosumers* that can manage their demand more efficiently to increase their *self-consumption* and *self-sufficiency* ratios [2]. Furthermore, the advancement of technologies (e.g., deployment of smart meters) and communication infrastructure enable bidirectional communication between utility and prosumers, which open up new opportunities for local energy markets [3].

The Clean Energy Package by the European Commission released in 2016 introduces new electricity market designs to enhance the role of end-users organized in energy communities [4]. The specific characteristics of energy communities vary depending on the local regulatory framework established by

each European Union Member State [5]. In this paper, we adopt the definition of an energy community based on the collective self-consumption framework in France [6], which defines an energy community as a group of households in close-proximity (within 1 km radius) connected to the low-voltage (LV) grid and able to collectively exchange and share energy. The members organize themselves around a legal entity, called “organizing legal person” (*Personne Morale Organisatrice* (PMO) in French) who is in charge of the overall activities of the community. The PMO connects the community members (i.e., households/prosumers) with the utility and other third-party stakeholders. More importantly, the PMO is responsible for determining the share of locally produced energy that is allocated to each participant on a 30 minute basis. This share is computed in the form of coefficients denoted as *keys of repartition*, which are then forwarded to the utility/distribution system operator (DSO) who further validates the energy exchange based on the households' smart meter measurements [7].

Such energy communities can be typically managed either in a centralized way [8], or as centralized or distributed markets according to [9]. On one hand, a traditional centralized platform consists in a single controller or market operator as in [4], [10] has the risk of privacy issues, since the community manager can directly access the prosumers' assets and data. On the other hand, a distributed decision mechanisms, for instance relying on alternating direction method multipliers (ADMM), allow leveraging those privacy concerns, due to the limited amount of exchanged information [11], [12].

One identified limitation of the current literature on community market is that the grid constraints are oftentimes neglected [8], or embedded with oversimplified models [11], [13]. Nonetheless, a high penetration of DERs (e.g., PV) in LV grid could lead to many technical issues, especially overvoltage problems [13]–[15]. Although several works on local energy market have overcome this technical challenge by considering grid constraints in their market model [15]–[17], their market models are not community-based.

Another current challenge faced by industry, particularly in France, is to determine attractive energy allocation rules (i.e., the *keys of repartition*) that can incentivize participant to join a community. Conventionally, the French DSO has proposed two methods to determine the keys of repartition, which are static and dynamic methods that do not fairly allocated among the participants [7]. An integrated framework for long-term

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and short-term planning of solar and storage collective that build upon French context is proposed in [18]. However, their work does not focus on real-time market operation and grid constraints/services are not considered.

Lastly, uncertainty in energy supply and demand become one of the main implementation challenges of local energy markets [19]. Multi-Stages strategies have shown to be the suitable approaches to address those uncertainties [4], [19], [20]. Nevertheless, none of the proposed strategies or other studies in the literature took into account all the aforementioned challenges of deploying an energy community.

Therefore, this paper proposes a management strategy for a local energy community of a group of residential households with PV and ESS. The strategy proposed in this work is adopted based on the actual community demonstrator in France, deployed by our industrial partner¹. The goal is to cover both technical and economic challenges related to the deployment of an energy community. To that extent, a three-stage management strategy is proposed, where we incorporate a day-ahead (DA) and real-time (RT) operation in the community. Furthermore, a penalty/reward scheme is proposed in order to incentivize households to be more predictable, and to participate in voltage regulation. Finally, the proposed strategy achieves an average of 30% individual cost reduction compared to the base scenarios and based on the considered test case that consists of 55 households. The main contributions of this paper are summarized as follow:

- A distributed commitment problem for the minimization of the day-ahead bill. In which households' privacy can be preserved.
- A real-time operation strategy to mitigate forecast uncertainties and voltage deviations.
- A methodology to fairly allocate the community energy (i.e., *the keys of repartition*) while ensuring a cost reduction/revenue improvement for each individual household.

Although this work is adopted based on the French context, we would like to highlight that the proposed strategy is generic and can be applied to any energy community under the European Renewable Energy Directive definition [21]. The methodology can also be used to establish an energy community in a residential neighbourhood or microgrid with local generations.

The remainder of this paper is organized as follows. Section II describes the considered system models, including community, households and grid model. Section III describes the generic methodology to solve the problems in a distributed way. The proposed three-stage community market management strategy is described in Section IV. The methodology is simulated and compared in Section V and Section VI concludes the paper.

II. MODEL DESCRIPTION

Let $\mathcal{H} = \{1, \dots, H\}$ be the set of households in the community. Let $\mathcal{D} = \{1, \dots, D\}$ be the set of days over a month with $\mathcal{T}_m = \{0, \Delta t_m, \dots, (|\mathcal{T}_m| - 1)\Delta t_m\}$ and

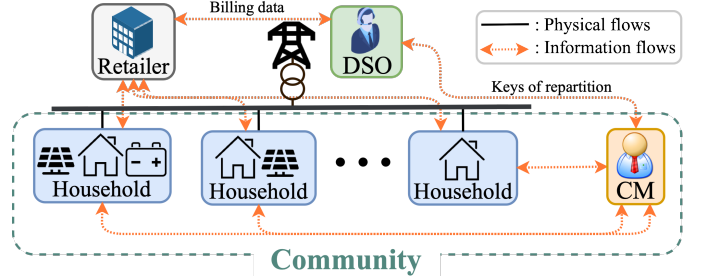


Fig. 1. Illustration of the considered energy community framework.

$\mathcal{T}_r = \{0, \Delta t_r, \dots, (|\mathcal{T}_r| - 1)\Delta t_r\}$ denote the considered market time interval with the time step of $\Delta t_m = 30$ minutes and real-time operation interval with the time step of $\Delta t_r = 5$ minutes, respectively. In Section IV, the obtained scalars/vectors/matrices from different stages are written with additional superscript, i.e., ^{DA} from DA operation and ^{RT} from RT operation. The models presented in this section are the generic ones (without the superscript).

A. Community Model

In this work, we introduce a Community Manager (CM), who is a third-party entity that has the role of a PMO. The proposed CM is responsible for maintaining the safe operation of the grid (i.e., prevent any voltage violations) in real-time and computing the households' energy bill as well as forwarding the *keys of repartition* to the DSO at the end of the month. The traditional retailer on the other hand, acts as a complementary energy supplier in addition to the energy community. As opposed to the CM, the retailer does not have access to households' measurements data, and it receives all billing information (i.e., the total amount of energy traded by each household to the retailer) from the DSO.

Fig. 1 shows the structure and the interaction between households, the CM and the DSO as well as the retailer. Each household comprises of smart meters that can perform measurements (e.g., voltage, power flow), and an energy management system. Furthermore, households actively coordinates with the CM to solve the global community problem in both DA and RT phases. This two-way communication can be provided by the smart meters [22] or through dedicated communication infrastructure. In the real application, however, households' computational and communication capability are limited due to the investment costs. Therefore, all computations and coordinations within the community that will be introduced in the next sections are formulated as convex optimization problems, such that the computational time and the optimality of the solutions can be achieved.

The considered energy community enables households to trade energy in addition to conventional energy purchase/sell from/to traditional retailers. It offers more attractive rates (π_t^{cm+}, π_t^{cm-}) than the retailers' (π_t^{gd+}, π_t^{gd-}), in which households can benefit from lower purchasing cost ($\pi_t^{cm+} \leq \pi_t^{gd+}$) and higher selling rate ($\pi_t^{cm-} \geq \pi_t^{gd-}$). The community also puts forward simplicity in energy pricing, where they are fixed and predetermined by the CM. Such simplicity is

¹Industrial partner 1: Beoga (<https://beoga.fr>)

highlighted as one important practice to achieve healthy energy collectives [23].

Let $p_{h,t}^{net}$ be the power dispatch/the power flowing through the meter of household h at time t . This physical flow can be decomposed into four different ‘‘contractual power’’ as (1).

$$p_{h,t}^{net} = p_{h,t}^{gd^+} + p_{h,t}^{cm^+} - p_{h,t}^{gd^-} - p_{h,t}^{cm^-} \quad (1)$$

where $p_{h,t}^{gd^+}$ and $p_{h,t}^{cm^+}$ denote the amount of power purchased by household h at time t from the retailer and the community respectively. Similarly, $p_{h,t}^{gd^-}$ and $p_{h,t}^{cm^-}$ denote the amount of power sold by household h at time t to the retailer and the community respectively. A household cannot buy and sell simultaneously, hence $p_{h,t}^{gd^-}, p_{h,t}^{cm^-} = 0$ when buying and $p_{h,t}^{gd^+}, p_{h,t}^{cm^+} = 0$ when selling. The amount of energy traded in the community at time t shall ensure the *community balance* (2).

$$\Omega_t = \underbrace{\sum_{h \in \mathcal{H}} p_{h,t}^{cm^+}}_{\text{importers/buyers}} = \underbrace{\sum_{h \in \mathcal{H}} p_{h,t}^{cm^-}}_{\text{exporters/sellers}} \quad (2)$$

where Ω_t denotes the total power allocated/energy traded in the community at time t . Eq. (2) ensures the total allocated power match the community supply and demand. The allocation on the overall community power to each household is determined through the computation of the *keys of repartition*, both for the buyers ($\lambda_{h,t}^+$) and the sellers ($\lambda_{h,t}^-$). For the buyers, it is defined as the ratio of individually demanded power from the community at time t , expressed in (3). While for the sellers, it is defined as the ratio of individually supplied power to the community at time t , expressed in (4).

$$\lambda_{h,t}^+ = \frac{p_{h,t}^{cm^+}}{\Omega_t} \quad ; \quad \sum_{h \in \mathcal{H}} \lambda_{h,t}^+ = 1 \quad (3)$$

$$\lambda_{h,t}^- = \frac{p_{h,t}^{cm^-}}{\Omega_t} \quad ; \quad \sum_{h \in \mathcal{H}} \lambda_{h,t}^- = 1 \quad (4)$$

B. Household Model

In this work, a household is considered as a non-flexible load and potentially equipped with DER(s) (i.e., PV and/or ESS). Let $p_{h,t}^{PV}$ and $\bar{p}_{h,t}^{PV}$ be the active power production and the maximum available active power production based on the irradiance of house h at time t . The PV operating points in a P, Q domain are described in (5) [24]:

$$0 \leq p_{h,t}^{PV} \leq \bar{p}_{h,t}^{PV} \quad (5a)$$

$$(q_{h,t}^{PV})^2 \leq (s_h^{PV})^2 - (p_{h,t}^{PV})^2 \quad (5b)$$

$$|q_{h,t}^{PV}| \leq \tan(\theta_h) p_{h,t}^{PV} \quad (5c)$$

where s_h^{PV} and θ_h denote the apparent power rating and the predefined power angle of PV in household h , while $q_{h,t}^{PV}$ denotes its corresponding reactive power production. For household with ESS, $soc_{h,t}$ is the ESS state of charge (SoC) based on the ESS’ capacity e_h^{st} , which shall always be maintained between \underline{soc}_h and \overline{soc}_h (6).

$$\forall t \in \mathcal{T} : \quad \underline{soc}_h \leq soc_{h,t} \leq \overline{soc}_h \quad (6)$$

The ESS power of household h at time t ($p_{h,t}^{st}$) can be decomposed as (7a), where $p_{h,t}^{st^+}, p_{h,t}^{st^-}$ denote the charging and discharging power. The constraints (7b) and (7c) give the limit to both powers, where $\bar{p}_h^{st^+}$ and $\bar{p}_h^{st^-}$ denote the maximum charging and discharging power respectively. Note that this paper considers the same maximum limit for both charging and discharging rated power for the ESS (i.e., $\bar{p}_h^{st^+} = \bar{p}_h^{st^-}$). Moreover, the ESS cannot be charged or discharged simultaneously. Thus, at each time t , either $p_{h,t}^{st^+} = 0$, or $p_{h,t}^{st^-} = 0$.

$$p_{h,t}^{st} = p_{h,t}^{st^+} - p_{h,t}^{st^-} \quad (7a)$$

$$0 \leq p_{h,t}^{st^+} \leq \bar{p}_h^{st^+} \quad (7b)$$

$$0 \leq p_{h,t}^{st^-} \leq \bar{p}_h^{st^-} \quad (7c)$$

Lastly, the SoC is updated by considering the charging ($\eta_h^{st^+}$) and discharging ($\eta_h^{st^-}$) efficiencies (in %) of the ESS (8).

$$soc_{h,t+\Delta t} = soc_{h,t} + \left(p_{h,t}^{st^+} \eta_h^{st^+} - \frac{p_{h,t}^{st^-}}{\eta_h^{st^-}} \right) \frac{100 \Delta t}{e_h^{st} 60} \quad (8)$$

Finally, for each time interval t , the net active and reactive power flow balance of each household $h \in \mathcal{H}$ are:

$$p_{h,t}^{net} = p_{h,t}^{load} - p_{h,t}^{PV} + p_{h,t}^{st} \quad (9)$$

$$q_{h,t}^{net} = q_{h,t}^{load} - q_{h,t}^{PV} + q_{h,t}^{st} \quad (10)$$

$$(s_h^{net})^2 \geq (p_{h,t}^{net})^2 + (q_{h,t}^{net})^2 \quad (11)$$

where \bar{s}_h^{net} denotes the maximum contractual apparent power of household h . For the household without PV or ESS, the corresponding $p_{h,t}^{PV}, q_{h,t}^{PV}$ or $p_{h,t}^{st}, q_{h,t}^{st}$ are obviously set to zero.

C. Grid Model

In this paper, a radial LV distribution grid is considered and represented as a graph $\mathcal{G}(\mathcal{N}, \mathcal{E})$ with N buses, where $\mathcal{N} = \{0, 1, \dots, N-1\} \supset \mathcal{H}$ and $\mathcal{E} := \{(i, j)\} \subset \mathcal{N} \times \mathcal{N}$ denote the set of buses and lines respectively. At each time t , let $v_{i,t}$ be the voltage of bus i ($v_{0,t} = 1$ p.u at the slack bus). Similarly, let $i_{ij,t}, p_{ij,t}$ and $q_{ij,t}$ be the current, active and reactive power flowing from bus i to bus j through the line (i, j) with resistance r_{ij} and reactance x_{ij} . In addition, let $\nu_{i,t}$ and $\ell_{ij,t}$ be the squared voltage of bus i and the squared current $i_{ij,t}$. The current for all links $(i, j) \in \mathcal{E}$ follows (12).

$$i_{ij,t}^2 = \ell_{ij,t} = \frac{p_{ij,t}^2 + q_{ij,t}^2}{\nu_{i,t}} \quad (12)$$

The radial LV grid is represented with typical DistFlow equations [25], expressed in (13).

$$p_{ij,t} = \sum_{k:(j,k) \in \mathcal{E}} p_{jk,t} + r_{ij} \ell_{ij,t} + p_{j,t}^{net} \quad (13a)$$

$$q_{ij,t} = \sum_{k:(j,k) \in \mathcal{E}} q_{jk,t} + x_{ij} \ell_{ij,t} + q_{j,t}^{net} \quad (13b)$$

$$\nu_{j,t} = \nu_{i,t} - 2(r_{ij} p_{ij,t} + x_{ij} q_{ij,t}) + (r_{ij}^2 + x_{ij}^2) \ell_{ij,t} \quad (13c)$$

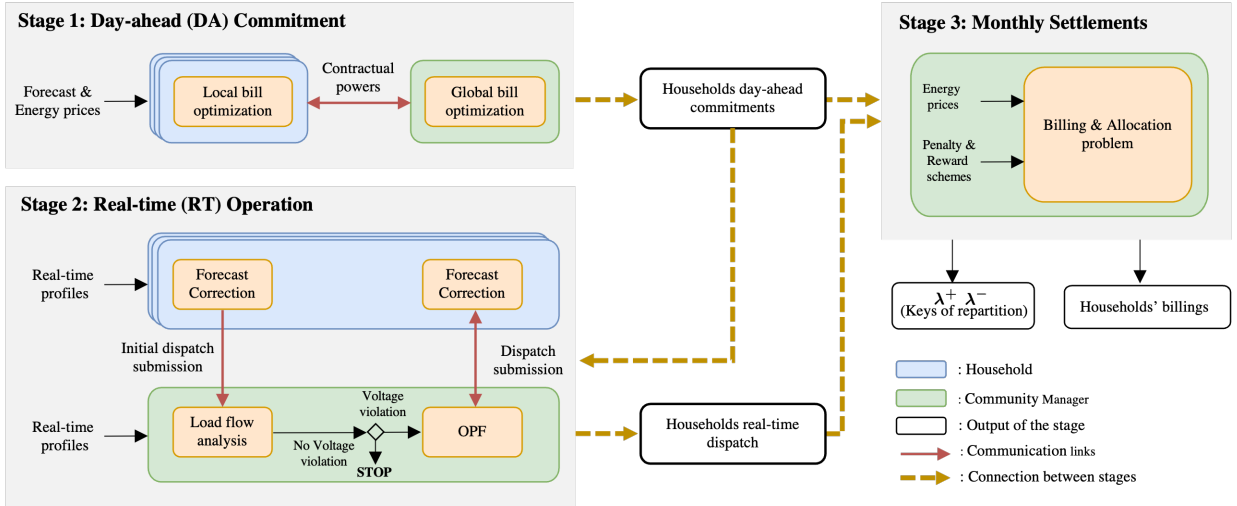


Fig. 2. Overview of the proposed three-stage community management strategy.

III. COMMUNITY COORDINATION AND DISTRIBUTED OPTIMIZATION

This section presents a generic formulation of the algorithm that solves the distributed problems in the proposed strategy introduced in the section IV. The motivations for the use of a distributed algorithm is to consider household heterogeneity with a scalable methodology. As will be presented in the next section, the CM does not have full controllability nor observability of the assets located behind-the-meter. It only measures the actual power flows at the meter level. Therefore, households' privacy and security can be preserved with the proposed methodology [26].

ADMM is proposed [11] to account the aforementioned considerations. This distributed algorithm solves the augmented Lagrangian of a convex optimization problem, by relying on local and global optimization, as well as dual variables updates [27]. It also relies on variables shared between households and the CM to iteratively solve the global community problem. A distributed problem is solved by the following iterative steps (iteration κ):

1) *Local optimization*: In the first step, each household h performs a local optimization to determine the optimal local variables ($\mathbf{x}_h^{(\kappa)}$) that will be submitted to the CM, by minimizing the following generic augmented Lagrangian (14).

$$\min_{\mathbf{x}_h^{(\kappa)}} f_h + \gamma_h^{(\kappa-1)} \cdot (\mathbf{x}_h^{(\kappa)} - \hat{\mathbf{x}}_h^{(\kappa-1)}) + \frac{\rho}{2} \left\| \mathbf{x}_h^{(\kappa)} - \hat{\mathbf{x}}_h^{(\kappa-1)} \right\|_2^2$$

Subject to: Household h local constraints (14)

where $\rho > 0$ denotes the ADMM convergence rate. $\hat{\mathbf{x}}_h^{(\kappa-1)}$ and $\gamma_h^{(\kappa-1)}$ denote the dual variables vector of household h that are obtained from the CM in the previous iteration. We refer to f_h as the main objective of household h (typically a minimization of energy bill). In this step, household will try to minimize f_h while driving the local variables $\mathbf{x}_h^{(\kappa)}$ to the same value as the global variables $\hat{\mathbf{x}}_h^{(\kappa-1)}$, since they refer to the same mathematical object. In a simpler definition, the global

variables $\hat{\mathbf{x}}_h$ can be interpreted as what the CM 'believes' of what the optimal value of local variables \mathbf{x}_h should be [28].

2) *Global/CM optimization*: Next, the CM collects all the local variables $\mathbf{x}_h^{(\kappa)}$ from the households to update the global variables $\hat{\mathbf{x}}_h^{(\kappa)}$ by solving the global problem (15).

$$\min_{\hat{\mathbf{x}}^{(\kappa)}} f_g + \sum_{h \in H} \gamma_h^{(\kappa-1)} \cdot (\mathbf{x}_h^{(\kappa)} - \hat{\mathbf{x}}_h^{(\kappa)}) + \frac{\rho}{2} \left\| \mathbf{x}_h^{(\kappa)} - \hat{\mathbf{x}}_h^{(\kappa)} \right\|_2^2$$

Subject to: CM/Global constraints (15)

where $\hat{\mathbf{x}}^{(\kappa)}$ aggregates $\hat{\mathbf{x}}_h^{(\kappa)} \forall h \in H$ and f_g denotes the main objective function considered by the CM that represents the global objective of the community. For instance, this common goal can be a minimization of collective community bill or other objectives that will be presented in the next section.

3) *Dual updates*: Lastly, the CM updates the dual variables.

$$\forall h \in \mathcal{H} : \quad \gamma_h^{(\kappa)} = \gamma_h^{(\kappa-1)} + \frac{\rho}{2} \left(\mathbf{x}_h^{(\kappa)} - \hat{\mathbf{x}}_h^{(\kappa)} \right) \quad (16)$$

The role of CM is similar to Walrasian auctioneer, where it iteratively matches the global and the local variables submitted by the households and stops until they reach the equilibrium/consensus state [11], i.e., the primal residual $\left\| \mathbf{x}_h^{(\kappa)} - \hat{\mathbf{x}}_h^{(\kappa)} \right\| \leq \epsilon$ and the dual residual $\left\| \hat{\mathbf{x}}_h^{(\kappa)} - \hat{\mathbf{x}}_h^{(\kappa-1)} \right\| \leq \epsilon$. In addition, the iterative process also stops when the maximum iteration κ_{\max} is reached.

To further simplify the formulations, the distributed problems described in the next section are written by expliciting the local and global objectives of both households and the CM (i.e., f_h and f_g) as well as their corresponding decision variables and constraints. By introducing those components, the problems then can be directly translated into their corresponding augmented Lagrangian, i.e., (14), (15), and solved using the distributed algorithm previously presented.

IV. THREE-STAGE MARKET MANAGEMENT STRATEGY

In this section, the proposed three-stage market management strategy is described. It consists of: (i) DA commitment of the power meter profiles based on individual and community

bill minimization, (ii) RT operation with uncertainties mitigation and voltage regulation and (iii) monthly settlements and billings with a fair reward/penalty scheme. Fig. 2 illustrates the information flows between the households and the CM as well as the inputs-outputs relations between the stages. The distributed problems are represented by two-edge arrows, with the local/global variables being the information that are exchanged between the households and the CM.

A. Stage 1: Day-ahead Commitment

In the first look ahead stage, each household in the community submits the contractual powers (1) profile it is committed to import/export on the next day on 30 min basis to the CM. The collective commitments would allow the CM to determine the expected amount of tradable energy in the community, and properly allocate them such that the collective households' energy cost can be minimized.

The DA commitment problem is formulated as a distributed problem and solved using the algorithm introduced in Section III. Prior to day d , each household h shall firstly determine its commitments by solving a *local bill optimization* problem (18) using load and PV forecast data, with the aim to minimize its expected energy bill of the next day by optimizing the operation of ESS. The decision variables considered by each household are stored in the following vector \mathbf{x}_h^{DA} (17).

$$\mathbf{x}_h^{\text{DA}} = \underbrace{(p_{h,t}^{\text{st}+}, p_{h,t}^{\text{st}-}, \text{soc}_{h,t})}_{\text{ESS variables}}, \underbrace{(p_{h,t}^{\text{gd}+}, p_{h,t}^{\text{cm}+}, p_{h,t}^{\text{gd}-}, p_{h,t}^{\text{cm}-})}_{\text{contractual powers}} \mid t \in \mathcal{T}_m^d)^{\text{DA}} \quad (17)$$

where $\mathcal{T}_m^d \subset \mathcal{T}_m$ is the set of 30 min time interval in the day d and the contractual powers are considered as the local/global variables (i.e., correspond to the \mathbf{x}_h and $\hat{\mathbf{x}}_h$ in Section III), which are exchanged between the households and the CM in the distributed mechanism. Note that this stage does not consider reactive power flows and the grid model, in order to avoid additional complexity that may exponentially increase the computational time [29].

For each household h , the *local bill optimization* is formulated as a local problem (14), with the main objective f_h^{DA} being the sum of the expected energy bill of the next day. This bill consists of the energy traded by the household to the community and the retailer at each 30 min interval (18a).

$$f_h^{\text{DA}} = \sum_{t \in \mathcal{T}_m^d} \begin{bmatrix} p_{h,t}^{\text{gd}+\text{DA}} \\ p_{h,t}^{\text{cm}+\text{DA}} \\ p_{h,t}^{\text{gd}-\text{DA}} \\ p_{h,t}^{\text{cm}-\text{DA}} \end{bmatrix} \cdot \begin{bmatrix} \pi_t^{\text{gd}+} \\ \pi_t^{\text{cm}+} \\ -\pi_t^{\text{gd}-} \\ -\pi_t^{\text{cm}-} \end{bmatrix} \frac{\Delta t_m}{60} \quad (18a)$$

Subject to: (1), (5) – (11) (Household constraints).

$$\text{soc}_{h, \max(\mathcal{T}_m^d) + \Delta t_m}^{\text{DA}} \geq \text{soc}_h^0 \quad (18b)$$

Additional ESS constraint (18b) is defined to maintain the SoC at least to be at its initial value soc_h^0 at the end of the day.

The CM then collects and validates the households' commitments by solving a *global bill optimization* problem (19), with the aim to minimize the overall households' energy bill while respecting the *community balance* (2). This problem

is formulated as a global problem (15), with the decision variables ($\hat{\mathbf{x}}^{\text{DA}}$) consist of the households' contractual powers.

$$f_g^{\text{DA}} = \sum_{h \in \mathcal{H}} \sum_{t \in \mathcal{T}_m^d} \begin{bmatrix} \hat{p}_{h,t}^{\text{gd}+\text{DA}} \\ \hat{p}_{h,t}^{\text{cm}+\text{DA}} \\ \hat{p}_{h,t}^{\text{gd}-\text{DA}} \\ \hat{p}_{h,t}^{\text{cm}-\text{DA}} \end{bmatrix} \cdot \begin{bmatrix} \pi_t^{\text{gd}+} \\ \pi_t^{\text{cm}+} \\ -\pi_t^{\text{gd}-} \\ -\pi_t^{\text{cm}-} \end{bmatrix} \frac{\Delta t_m}{60} \quad (19)$$

Subject to: (2) (Community balance).

B. Stage 2: Real-time Operation

The second stage emphasises on real time control with regards to grid constraints and services. In particular, the motivations in *Stage 2* are to mitigate any uncertainties (i.e., deviation of household net power with the commitment and due to load and PV forecast error) and possible voltage violations in real-time operation, with a finer time resolution Δt_r of 5 min and while considering grid constraints.

The accuracy of households' commitments in the actual operation is an important factor to achieve optimal economic benefit among the community users, because any deviation in real-time may impact the energy that can be allocated in the community (previously settled in the *stage 1*). Predictability could also bring additional value to the community, for instance, the CM can possibly provide complementary services to the DSO by being collectively predictable [30].

Moreover, as the grid model is not considered in *stage 1*, the voltage quality in the RT operation thus cannot be guaranteed. If voltage violations occur in the actual operation, some households may have to limit their local production or consumption, leading to additional cost incurred for these particular users.

The RT operation consists of two steps (Fig. 2) and two possible scenarios, i.e., with or without voltage violation.

1) *Forecast Correction*: Firstly, households use their DERs to mitigate any mismatch between the actual and the committed dispatch, to prevent paying the penalty to the CM due to the non-respected commitments (further introduced in *Stage 3*). Thus, prior to the RT operation $t \in \mathcal{T}_r$, each household h submits the initial power it is going to dispatch ($p_{h,t}^{\text{netRT}^0}$) for the next time step t to the CM, by solving the *forecast correction* problem (20), i.e., mismatch minimization between the actual and committed DA dispatch.

$$\min_{\mathbf{x}_h^{\text{RT}^0}} \left(p_{h,t}^{\text{netDA}} - p_{h,t}^{\text{netRT}^0} \right)^2 \quad (20a)$$

Subject to: (5) – (11) and (20b) (Household constraints).

$$\text{soc}_{h,t}^{\text{DA}} - \delta_{\text{soc}} \leq \text{soc}_{h,t}^{\text{RT}^0} \leq \text{soc}_{h,t}^{\text{DA}} + \delta_{\text{soc}} \quad (20b)$$

The vector $\mathbf{x}_h^{\text{RT}^0} = (p_{h,t}^{\text{net}}, p_{h,t}^{\text{PV}}, q_{h,t}^{\text{PV}}, p_{h,t}^{\text{st}+}, p_{h,t}^{\text{st}-}, \text{soc}_{h,t}, q_{h,t}^{\text{st}})^{\text{RT}^0}$ aggregates the decision variables that represent the household's dispatch and the operating setpoints of its DERs. Additional operational flexibility of the ESS is proposed (20b), where the ESS can be operated with a RT reserve $\pm \delta_{\text{soc}}$ (in %) around the scheduled SoC profile that have been determined in the DA (Fig. 3). Such flexibility would prevent the ESS to be over-charged/discharged, so that the SoC level can be maintained throughout the day, and most importantly during the peak hours.

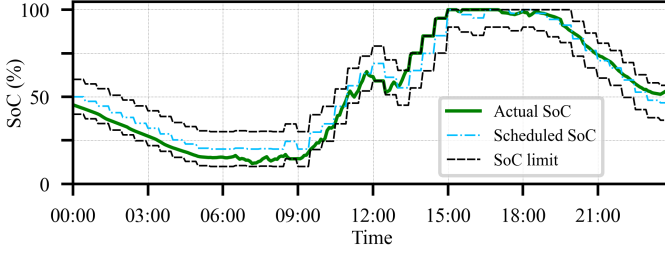


Fig. 3. ESS real-time operation over a particular day.

2) *Voltage Verification/Control*: The CM then collects households' initial submission $p_{h,t}^{netRT^0}$ and performs validation using a load flow calculation. If no potential voltage violations are predicted, the CM confirms the households' submissions for the time $t \in \mathcal{T}_r$ (21).

$$\forall h \in \mathcal{H} : p_{h,t}^{netRT} = p_{h,t}^{netRT^0} \quad (21)$$

However, if any bus voltage violation is detected, a second control step with voltage control is formulized as a multi-objective optimal power flow (OPF) problem with second-order conic programming (SOCP) relaxation, adopted from previous works [31]. Moreover, it is formulized as a distributed problem, with the local/global variables of household h corresponding to the actual RT power dispatch ($p_{h,t}^{netRT}$).

The voltage control starts by each household h submitting the new RT power dispatch ($p_{h,t}^{netRT}$) to the CM. This submission is formulized as a local problem (14), with the vector $\mathbf{x}_h^{RT} = (p_{h,t}^{net}, p_{h,t}^{PV}, q_{h,t}^{PV}, p_{h,t}^{st+}, p_{h,t}^{st-}, soc_{h,t}, q_{h,t}^{st})^{RT}$ aggregates the considered decision variables, and the main objective (f_h^{RT}) and constraints are formulized as in (22).

$$f_h^{RT} = (p_{h,t}^{netDA} - p_{h,t}^{netRT})^2 \quad (22)$$

Subject to: (5) – (11), (20b) (Household constraints).

Households still aim to minimize the forecast mismatch because any voltage control action may lead to forecast deviations, which will incur additional penalty costs (introduced further in *Stage 3*). Households utilize their ESS reserve in real-time as the control action, or perform additional PV curtailments in case of inadequate reserve.

The CM then validates households' submissions by solving the OPF to mitigate the voltage violations. The OPF is formulized as a global problem (15) (i.e. at the coordination level) with the decision variables vector ($\hat{\mathbf{x}}^{RT}$) consisting of the households' submissions and the grid state variables (e.g., bus voltage, branch current and power). The main objective of the OPF problem (f_g^{RT}) and its constraints are shown in (23).

$$f_g^{RT} = \theta_n \sum_{h \in \mathcal{H}} \underbrace{(p_{h,t}^{netDA} - \hat{p}_{h,t}^{netRT})^2}_{\text{Commitment mismatch}} + \theta_l \sum_{(i,j) \in \mathcal{E}} \underbrace{\ell_{ij,t} r_{ij}}_{\text{Grid losses}} \quad (23a)$$

Subject to: (11) (Household limit), (13) (DistFlow Eqs.)

$$\forall (i,j) \in \mathcal{E} : \ell_{ij,t} \geq \frac{p_{ij,t}^2 + q_{ij,t}^2}{\nu_{i,t}} \quad (23b)$$

$$\forall i \in \mathcal{N} : \underline{\nu}_{i,t}^2 \geq \nu_{i,t} \geq \bar{\nu}_{i,t}^2 \quad (23c)$$

The OPF aims to minimize the global forecast mismatch and grid losses, with $\theta_l, \theta_n, \in [0, 1]$ being the controller parameters that weight the two objectives. Note that, these weighting parameters have to be tuned properly to ensure the feasibility and the desired operating point of the algorithm [31]. The SOCP relaxation convexifies the equality relation of the current (23b) by transforming it into inequality relation [25]. Furthermore, (23c) ensures that the bus voltage remains within the limits, with $\underline{\nu} = 0.95$ and $\bar{\nu} = 1.05$.

The final solutions of this stage are households' initial submissions ($p_{h,t}^{netRT^0}$) and the actual RT dispatch ($p_{h,t}^{netRT}$) that will be used in the bill calculation in *stage 3*.

C. Stage 3: Monthly settlement and billing

At the end of the month, the CM is responsible to optimally allocate the community energy to the households based on the DA and RT operations. By determining the *keys of repartition* ($\lambda_{h,t}^+, \lambda_{h,t}^-$), the energy bill of each household can be computed. It consists of: (i) energy trading cost with the retailer and community, (ii) penalty fees due to unsatisfied commitment and (iii) rewards for participating in the voltage control.

1) *Energy trading cost*: The energy trading component in households' bill is computed based on the actual RT dispatch and integrated on a 30 min basis. The amounts of energy imported and exported by household h during a time $t \in \mathcal{T}_m$ are computed by averaging the RT dispatch as (24) and (25).

$$B_{h,t} = \underbrace{\max(0, \frac{\sum_{t_r \in \mathcal{I}_t} p_{h,t_r}^{netRT}}{|\mathcal{I}_t|})}_{\text{importer/buyer}} \quad (24)$$

$$S_{h,t} = \underbrace{\left| \min(0, \frac{\sum_{t_r \in \mathcal{I}_t} p_{h,t_r}^{netRT}}{|\mathcal{I}_t|} \right|}_{\text{exporter/seller}} \quad (25)$$

where $\mathcal{I}_t = \{t, t + \Delta t_r, \dots, t + \Delta t_m - \Delta t_r\}$ denotes the RT time interval between the market time t and $t + \Delta t_m - \Delta t_r$. The actual energy allocated to the community at time t then can be determined by (26), where it ensures the total allocated energy Ω_t match the community buyers and sellers.

$$\Omega_t = \min \left(\sum_{h \in \mathcal{H}} B_{h,t}, \sum_{h \in \mathcal{H}} S_{h,t} \right) \quad (26)$$

Based on $B_{h,t}, S_{h,t}$ and the allocated community energy Ω_t , the energy trading cost of each household h at time t can be calculated. Firstly, the cost of energy traded with the community ($C_{h,t}^{cm}$) is expressed in (27a), where it depends on the *keys of repartition*. The remaining energy then is traded with the retailer, with its cost ($C_{h,t}^{gd}$) expressed in (27b). Finally, the total energy trading cost can be calculated as (27c).

$$C_{h,t}^{cm} = \left(\underbrace{\lambda_{h,t}^+ \Omega_t \pi_t^{cm+}}_{\text{imported/purchased}} - \underbrace{\lambda_{h,t}^- \Omega_t \pi_t^{cm-}}_{\text{exported/sold}} \right) \delta t_m \quad (27a)$$

$$C_{h,t}^{gd} = \left[\underbrace{(B_{h,t} - \lambda_{h,t}^+ \Omega_t) \pi_t^{gd+}}_{\text{imported/purchased}} - \underbrace{(S_{h,t} - \lambda_{h,t}^- \Omega_t) \pi_t^{gd-}}_{\text{exported/sold}} \right] \delta t_m \quad (27b)$$

$$C_{h,t}^{td} = C_{h,t}^{cm} + C_{h,t}^{gd} \quad (27c)$$

2) *Penalty Cost*: The penalty cost due to uncertainties is computed based on the difference between the committed and the actual energy dispatch (28), with π^{dev} denotes the penalty price (in c€/kWh).

$$C_{h,t}^{dev} = \left| p_{h,t}^{netDA} - \frac{\sum_{t_r \in \mathcal{I}_t} p_{h,t_r}^{netRT}}{|\mathcal{I}_t|} \right| \pi^{dev} \frac{\Delta t_m}{60} \quad (28)$$

3) *Grid Service Rewards*: The reward for voltage regulation is computed by comparing the actual RT dispatch ($p_{h,t}^{netRT}$) with the initial RT submission ($p_{h,t}^{netRT^0}$), since the initial submission is expected as the optimal dispatch in the RT operation (i.e., the dispatch with the minimal forecast mismatch) (29).

$$C_{h,t}^{gs} = \frac{\sum_{t_r \in \mathcal{I}_t} (p_{h,t_r}^{netRT^0} - p_{h,t_r}^{netRT})}{|\mathcal{I}_t|} \pi^{gs} \frac{\Delta t_m}{60} \quad (29)$$

where π^{gs} denotes the grid service reward (in c€/kWh). For simplicity reason, both π^{dev} and π^{gs} are fixed over time. Finally, the total cost for each household h at time $t \in \mathcal{T}_m$ is:

$$C_{h,t} = C_{h,t}^{td} + C_{h,t}^{dev} + C_{h,t}^{gs} \quad (30)$$

In the actual transactions, households will pay the CM for the penalties and the energy purchased from the community. On the other hand, the CM will reward the households and pay them for their energy exported to the community. This CM's cash flow can be modelled as community budget balance (31).

$$\sum_{h \in \mathcal{H}} \sum_{t \in \mathcal{T}} C_{h,t}^{cm} + C_{h,t}^{dev} + C_{h,t}^{gs} = \text{surplus} \quad (31)$$

The community surplus in (31) can be represented and utilized by the CM in different ways. For instance, the CM can set the surplus for its personal revenue or investments, by adjusting the difference between the buying and selling prices. It may also be used to cover any external costs (e.g., operational costs) or to allocate additional benefits to the community members differently over the community lifetime.

The optimal billing is ultimately formulated as an optimization problem (32) with the *keys of repartition* (at each 30 min in the month) being the decisions variables ($\lambda_{h,t}^+$, $\lambda_{h,t}^-$). The objective is to minimize the deviation between the actual bill and the day-ahead predicted cost (over a month).

$$\min_{\lambda_{h,t}^+, \lambda_{h,t}^- | h \in \mathcal{H}, t \in \mathcal{T}_m} \sum_{h \in \mathcal{H}} \left(\frac{\sum_{t \in \mathcal{T}_m} C_{h,t}^{DA} - C_{h,t}}{\sum_{t \in \mathcal{T}_m} C_{h,t}^{DA}} \right)^2 \quad (32a)$$

subject to:

$$(1) - (4), (24) - (26) \text{ (Community Cons.)}$$

$$(27) - (31) \text{ (Billing Cons.)}$$

$$\forall h \in \mathcal{H} : \sum_{t \in \mathcal{T}_m} C_{h,t} \leq \sum_{t \in \mathcal{T}_m} B_{h,t} \pi_t^{gd+} - S_{h,t} \pi_t^{gd-} \quad (32b)$$

where $C_{h,t}^{DA}$ represents the expected total household's h cost at time t based on *stage 1* (i.e. with uncertainties and grid constraints neglected). Additionally, (32b) is proposed to limit household's total cost and ensure it will not be higher than a conventional case where households trade their energy fully with the retailers.

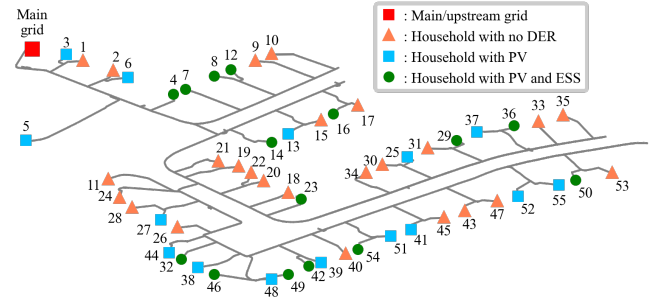


Fig. 4. The considered IEEE European LV Test Feeder with 55 households.

In the proposed *allocation* problem (32), the CM can freely set the community surplus in (31) or the penalty deviation price (π^{dev}) as well as the grid service price (π^{gs}) can either be optimization parameters or variables. This topic will be discussed further in the next section.

V. CASE STUDY

The proposed community management strategy is firstly applied to the IEEE European LV Test Feeder [32] with 55 households, as shown in Fig. 4. The loads are assumed to have a constant power factor of 0.95. The DERs have unity power factor and their nominal capacities are randomly selected, which are between 5 and 10 kWp for the PV, and between 5kW/10kWh and 10kW/20kWh for the ESS. The PV profiles are adopted from real irradiance data in Grenoble, France. For all households with ESS, the SoC is maintained between 20 % to 100 % and ensured to be at least 40 % at the end of the day (determined in *stage 1*). For the RT operation, all ESSs are set to have an operational margin of $\delta_{soc} = 10\%$.

In the considered test case, the retailer buying price (π_t^{gd+}) follows Time-of-Use (ToU) pricing, which are 7.97 c€/kWh and 11.75 c€/kWh outside and during the peak hours. The retailer selling price (π_t^{gd-}) is fixed to 6.5 c€/kWh [33]. The CM set the community prices to 7.5 c€/kWh and 7 c€/kWh for the buying (π_t^{cm+}) and selling price (π_t^{cm-}) respectively.

The proposed methodology is evaluated and compared with two base scenarios. In both scenarios, households can only trade energy conventionally with the retailer (i.e., there is no community). Households optimize their ESS independently in day-ahead by solving a *bill optimization* problem (18a) that considers retailer's prices only. The same real-time discretization ($\Delta t_r = 5$ min) is considered for both scenarios. The main difference between those two scenarios lies in the real-time voltage management strategy:

- 1) *Base scenario 1*: The DSO will send a power dispatch limit (at the meter level) to each household in real-time. The dispatch limits are obtained by solving an OPF (23) that minimizes the grid losses.
- 2) *Base scenario 2*: Households are limited to export ≤ 3 kW. This value is selected based on a preliminary assessment on the test system.

In both base scenarios, each household shall respect the power limitation and act by utilizing its ESS' real-time reserve or performing additional PV curtailments if the reserve is not sufficient.

A. Convergence of the Proposed Distributed Algorithm

TABLE I
COMPUTATIONAL TIME OF THE PROPOSED STAGES.

	Stage 1	Stage 2: Without VC	Stage 2: With VC	Stage 3
Computational time (s)	188	0.8	60	13.33

All the simulations are evaluated on a computer with an Intel® Core™ i3-4030U processor and 8 GB of RAM. The proposed models are formulated in Python and solved using Gurobi 9.1. Table I summarizes the computational time for all stages and highlights that the proposed strategy is shown to be considerably fast and feasible for implementation, especially for the RT operation that requires faster computational speed (5 min control intervals). Although communication delay is neglected in the simulations, the proposed algorithm converged in relatively small numbers of iterations compared to other literatures [24], [28], as shown by the evolution the residuals of in Fig. 5.

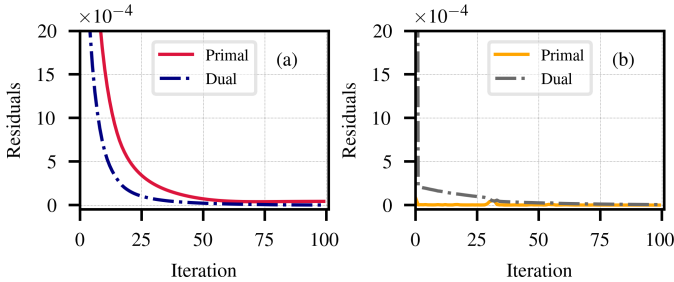


Fig. 5. The primal and dual residuals of one (a) DA and (b) RT problems.

B. Economic Performance Assessment

In this assessment, the community surplus (31) is set to zero, meaning all the money received by the CM will be fully allocated to the households. Furthermore, the penalty price (for RT power deviations) is set to $\pi^{dev} = 1 \text{ c€/kWh}$ and the grid service price (for voltage regulation) is set to $\pi^{gs} = 30.1 \text{ c€/kWh}$, which is significantly higher than the penalty price and the actual energy prices. The voltage regulation is illustrated for a specific node on Fig. 6, which also justifies that the proposed RT operation can effectively maintain the voltage close to the upper limit.

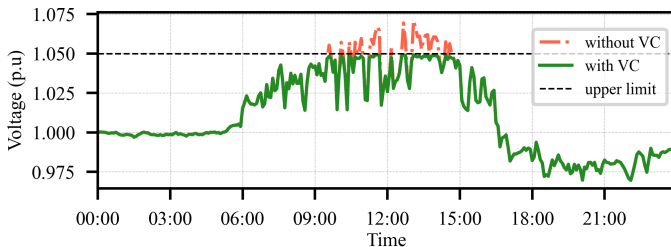


Fig. 6. Voltage profile comparison with and without voltage control (VC).

The allocated energy in the community (*keys of repartition*) over a particular day is shown in Fig. 7. Most of the energy

traded in the community occurs in the daytime during high PV production levels. Less energy is traded in the community after 18:00, because of the low PV production and households that have to maintain their ESS SoC until the end of the day.

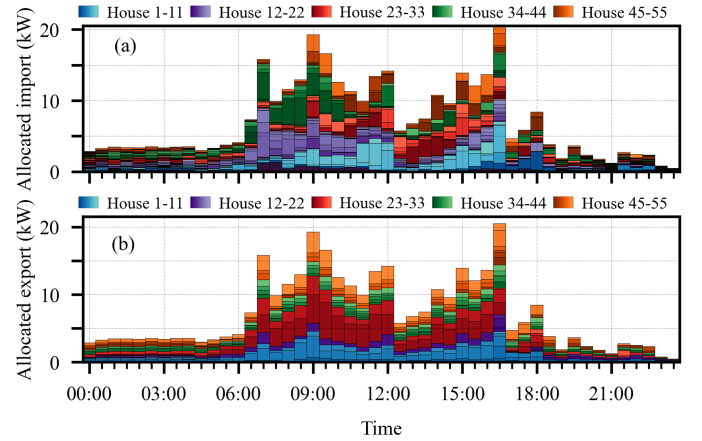


Fig. 7. The keys of repartition of (a) buyers, (b) sellers over a particular day.

The total costs and revenue of the combined households are compared in Fig. 8(a). The proposed community management reduces the overall households' costs by around 4% compared to both base scenarios. Moreover, it increases the overall households' revenue by 5% and 6.5% compared to the first and second base scenario respectively. This increase is allowed with more energy exported in total in the proposed management strategy, as shown in Fig. 8(b). Especially, there are much less PV curtailments compared to the base scenarios thanks to a more efficient use of the ESS. Moreover, this improved storage usage leads to energy export (i.e., selling) during night-time and peak-hours, which is not the case in both base scenarios and ultimately increase further the revenue.

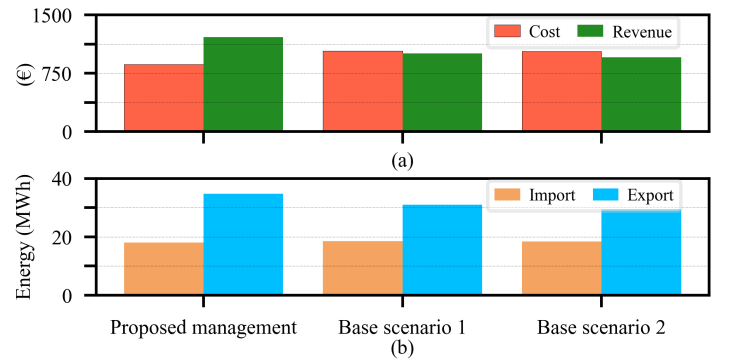


Fig. 8. Case comparisons: (a) cost and revenue, (b) energy import and export

The cost and revenue breakdown of the proposed community management is shown in Table II, which shows that the households still rely on the retailer, especially during the peak hours when the local productions are low. In terms of revenue, 66% of the overall combined households' revenue comes from the energy sold to the retailer due to the high penetration of DERs in the considered test case.

Fig. 9 shows the result in terms of individual economic performance. In overall, the proposed community management

TABLE II
TOTAL MONTHLY COST AND REVENUE BREAKDOWN.

Cost (€)			Revenue (€)		
Grid buying	Community buying	Penalty	Grid selling	Community selling	Reward
446	386.5	31.5	794.5	361	50.3

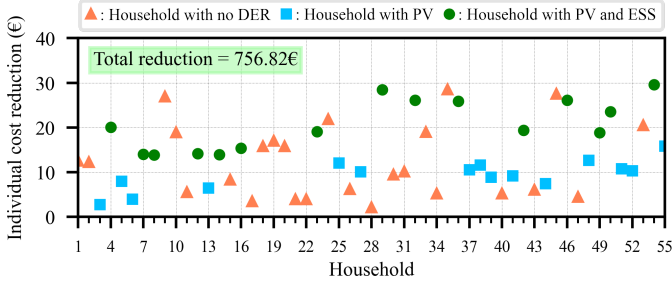


Fig. 9. Individual cost reduction among 55 households.

achieves a total of 756.82 € cost reduction compared to the base scenario 1. Individual households cost reduction is 30% on average, with a minimum of 7% over all the users. As a matter of fact, some households with DERs obtain a negative bill (i.e., receive money), from initially positive in both base scenarios.

C. Sensitivity Analysis

A sensitivity analysis is then performed to investigate the impact of the selection of π^{dev} and π^{gs} to the community surplus (31), by setting it as an additional optimization variable in (32). Fig. 10 displays the results of different settings of $\pi^{dev} \in [0, 35]$ and $\pi^{gs} \in [0, 80]$. The selection of $\pi^{dev} \geq 25$ makes the *allocation* problem (32) infeasible, because for some households, joining the community will increase their total costs. In other words, the constraint (32b) cannot be respected. The CM can maximize the surplus by setting the π^{dev} high and the π^{gs} low (the green area). However, this configuration will not be fair for all the community participants, especially for the ones who actively participate in the voltage regulations. As a result, households will receive less reward and benefit (less cost reduction) from the community.

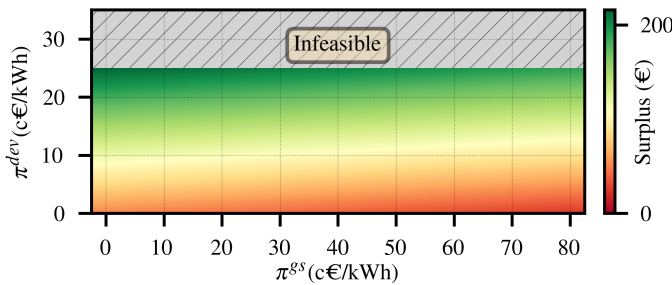


Fig. 10. The impact on π^{dev} and π^{gs} to the community surplus.

Therefore, this sensitivity analysis can help the CM to select the suitable π^{dev} and π^{gs} based on the expected community surplus. In addition, the CM has to anticipate the trade-off

between the surplus and the households' cost reduction, to ensure the attractiveness of the community. Further analysis on surplus maximization and households' cost reduction can be done by observing the different community buying and selling price. However, it is not the scope of this paper and it represents the immediate next step for the future works.

D. Scalability Tests of the Distributed Algorithm

In order to further validate the scalability of the proposed strategy, *stage 1* and *stage 2* are tested on three additional test systems comprising of 84, 117, and 135 households with the complete grid models available in [34]. In each test system, there are 50% shares of households with DERs – 25% with only PV and 25% with PV+ESS.

TABLE III
CONVERGENCE PARAMETERS OF DIFFERENT TEST SYSTEMS.

	Stage 1 (DA)		Stage 2 (RT)	
	Time (s)	Iterations	Time (s)	Iterations
55 Households (original test system)	188	58	50	60
84 Households	276	60	105	70
117 Households	372	62	160	75
135 Households	416	64	170	58

Table III compares the average computational time and number of iterations required to reach the convergence criteria for both DA and RT stages on the four different test systems. Results highlight that the distributed algorithm can converge reliably within a desirable time. Although the computational time is higher on the bigger system, it is however still within the acceptable time horizon, especially for the RT stage that should be computed every 5 min.

VI. CONCLUSION

In this paper, a three-stage management strategy for an energy community that considers grid constraints has been presented. Households can exchange energy to the community firstly by declaring their contractual energy commitments in day-ahead (DA). In real-time operation, the community manager coordinates with the households to oversee any uncertainties and possible voltage violations from the profiles settled in the DA. Simulation results showed that the proposed methodology reduces the energy cost and increases the revenue of the overall community members compared to the base cases by 16% and 20% respectively. Due to its collective nature, the proposed community has shown to allow 11% more energy produced by the combined local assets, compared to the base cases where the local assets are not collectively optimized. Moreover, the proposed methodology computes the energy allocated to each household (*keys of repartition*) and ensures individual cost reduction (30% on average). Furthermore, the proposed real-time operation is effective to maintain the grid voltage within the limit and the reward scheme could proportionally compensate the households participation in voltage control. The sensitivity analysis showed how the different penalty and grid service pricing schemes can influence the surplus in the community and the cost reduction among the

households, which can help the community manager to set the appropriate price for the penalty and the grid service reward. Finally, the scalability tests are presented and highlighted the applicability of the proposed methodology.

The work on this paper can be extended to several areas. Firstly, it could be interesting to study different settings of community prices (i.e., buying and selling price) and observe the impact on the overall community cost reduction and the community surplus. Secondly, integration of different technologies such as collective demand response and electric vehicles would possibly achieve better community performances. Finally, further research on the communication infrastructure is essential, as it should be considered in the computational feasibility of the proposed algorithms, especially for the real-implementation of the community.

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