A two-stage management strategy for the optimal operation and billing in an energy community with collective self-consumption

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Highlights

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- Four energy management strategies and ten options for energy allocation and billing
- A penalization of storage systems power variations in order to incur less degradation
- Community saving over 11 % compared to a baseline of individual self-consumption only
- Uniform members' bill reduction thanks to optimization-based benefit sharing strategy

A two-stage management strategy for the optimal operation and billing in an energy community with collective self-consumption

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Abstract

This study fits in the context of collective self-consumption in energy communities, where participants within a given area can exchange and trade energy among themselves. We propose a two-stage approach that decouples the operational phase, i.e., the energy management strategy (EMS), from the settlement where the energy is contractually allocated to the participants. In particular, this decoupled approach allows testing and comparing different methods for the EMS on one side and for the energy sharing on the other, for a total of forty different investigated combinations. Rule-based and optimization-based approaches are considered, allowing each community to compare and select the most appropriate management in line with its specification. The numerical results obtained on a real test case in France show 11.7 % saving on the global community bill compared to a case in which the members are not organized as a community. Also, specific allocation mechanisms proposed in this paper allow uniforming the savings in terms of individual bill reduction, which can further encourage end-users to join a community.

Keywords: Energy communities, Collective self-consumption, Energy management strategy, Optimization, Benefit allocation

1. Introduction

The increasing interest to move from the legacy power system to modern and decarbonized grids drives all players to join forces. From the end-user perspectives, the concept of energy communities (EC) and self-consumption makes it possible to contribute easily to the grid modernization by installing home scale system and exchanging energy between neighbors.

Although there are many definitions and concepts of EC [1] that may lead to confusion, the general adopted description is that it consists in the aggregation of several end-users – traditional consumers and/or prosumers (i.e., end-users that can act either as a producer or a consumer [2]). The main characteristics of EC are participatory, local and collective [3]. The implementation of EC in most countries is rather slow due to the lack of appropriate regulatory landscape [4] but it is expected to speed up in the coming years.

Different EC configurations are usually encountered in the literature. The simplest forms consist in a single shared asset (e.g., energy storage system) [5], while the most common architecture displays distributed photovoltaic (PV) and battery systems [6, 7], or other types of local generations [8].

The EC considered in this paper is regarded through the concept of collective self-consumption (CSC). Traditional individual self-consumption defines an operation where producers consume all or a part of the electricity generated by their own installation [9]. While traditional self-consumption refers to a single and independent end-user, the idea of CSC is to aggregate different production as well as consumption profiles in order to reach higher self-consumption ratios (SCR) thanks to heterogeneous energy usages.

In Denmark, Finland, and Sweden, CSC is currently allowed only in a limited way (e.g., via private grids) or tolerated within a regulatory framework [10]. France has started its CSC initiative in 2016 as stated in a governmental regulation [11] and targets 50 projects of CSC by 2023 [12].

A self-consumption operation is then considered collective whenever there are one or more producers and one or more consumers organized together around a legal entity called "Personne Morale Organisatrice (PMO)", in French, or "Moral Organizing Entity", and the points of energy delivery of all the members are located on the low voltage grid [11]. Also, a 2 km distance is set as the maximum geographical perimeter and a 3 MW maximum cumulative installed generation of the EC has been adopted [13].

In this context, individuals are presented space to play their part in the energy transition. Two challenges arise when dealing with the management of an EC under the CSC framework: i) the physical operation of assets (i.e., the energy management strategy, EMS) and ii) the contractual allocation of energy produced in the community to the different participants.

The development of EMS for such systems has long been addressed in the literature. [14] successfully achieved a higher SCR by optimizing the operation of a battery while [15] developed a self-consumption-based EMS for every prosumer in order to avoid overvoltages. [16] implemented a rule-based blockchain method that differentiates between scenarios of pure individual self-consumption and peer-to-peer (P2P) energy trading. Aggregated batteries in EC are scheduled on a rolling horizon basis with successive updates of forecast followed by a rule-based strategy that computes the real-time controls [17].

Beyond the optimal operation of the community assets, one

Nomenclature

Abbreviations

CSC	Collective self-consumption
DSO	Distribution system operator
EC	Energy community
EMS	Energy management strategy
EV	Electric vehicle
KoR	Keys of repartition
PMO	Moral organizing entity
PV	Photovoltaic
SCR	Self-consumption ratio
SoC	State of charge
SSR	Self-sufficiency ratio
$\mathcal{N}$	Set of participants in community, indexed by n
$\mathcal{S}$	A coalition of the grand coalition $\mathcal{N}$
$\mathcal{T}$	Set of time intervals, indexed by t
st	Storage type (battery or EV)

Symbols

α	Penalty factor for storage power variations
$\Delta P_t^{st^+}, \Delta P_t^{st^-}$	Positive and negative difference between storage st power output at time t and $t-1$
Δt	Simulation time step
$\lambda_{n,t}$	Keys of repartition applied to individual n at time t
μ_n^{st}	One trip efficiency of storage st of individual n
$\phi_{n,t}(\mathcal{N}, v)$	Shapley value of individual n at time t for the grand coalition $\mathcal{N}$ and the benefit v
$\pi_n^{buy,comm}, \pi_n^{buy,gd}$	Buying price in the community and the grid
$\pi_n^{sell,comm}, \pi_n^{sell,gd}$	Selling price in the community and the grid
$\Pi_n^{subs,gd}$	Subscription price in the grid
ρ_n^{st}	Penalty of storage st of individual n
$\xi P_{n,t}^{bat^+}$	Additional charge from community to the battery of individual n at time t in EMS_2 community rules
B_n	Overall bill of individual n
B_n^0	Overall bill of individual n for the baseline simulation
$B_n^{gd}, \mathcal{B}_n^{comm}$	Grid and community bill of individual n
C_n^{inv}	Investment cost of all assets of individual n
$E_{max,n}^{st}, P_{max,n}^{st}$	Energy and power capacity of storage st of individual n
f_1'	Objective function of optimization-based approaches in Stage 1 after penalty of storage
f_1	Objective function of optimization-based approaches in Stage 1 before penalty of storage
f_2	Objective function of optimization-based approaches in Stage 2
$P_{coll,t}^{prod}, P_{coll,t}^{cons}$	Collective production and consumption at time t
$P_{coll,t}^{selfcons}$	Collective self-consumption from the community at time t
$P_{coll,t}^{surplus}$	Collective surplus at time t
$P_{n,t}^{alloc}$	Power allocated from community to individual n at time t
$P_{n,t}^{comm^+}, P_{n,t}^{gd^+}$	Power imported from the community and the grid of individual n at time t
$P_{n,t}^{comm^-}, P_{n,t}^{gd^-}$	Power exported to the community and the grid of individual n at time t
$P_{n,t}^{comm}, P_{n,t}^{gd}$	Power exchanged contractually from/to the community and the grid of individual n at time t
$P_{n,t}^{indsc}$	Power individually self-consumed of individual n at time t
$P_{n,t}^{meter^+}, P_{n,t}^{meter^-}$	Power imported and exported at the meter of individual n at time t
$P_{n,t}^{meter}$	Power exchanged physically at the meter of individual n at time t
$P_{n,t}^{PV}$	PV production of individual n at time t
$P_{n,t}^{st^+}, P_{n,t}^{st^-}$	Storage st power charge and discharge of individual n at time t
$P_{n,t}^{st}$	Storage st power output of individual n at time t
P_n^{subs}	Subscription power of individual n
$SOC_{min,n}^{st}, SOC_{max,n}^{st}$	Minimum and maximum SoC level of storage st of individual n
$SoC_{n,t}^{st}$	SOC of storage st of individual n at time t
$v_t(\mathcal{S})$	Benefit or value of coalition $\mathcal{S}$ at time t

concern is to define the way the local generation is allocated to the different community participants. In the French context, the allocation of the overall community generation takes the form of coefficients denoted as *keys of repartition* (KoR) [18] that can be computed in many ways.

A traditional approach regarding such allocation mechanism in an EC consists in local markets and/or P2P trading [19]. A bi-level optimization that models a local market has been applied in [7, 20] with the lower level clearing the market while the upper level allocates the community energy among participants. The study in [18] proposed that the energy allocation should be performed on a yearly basis to ensure that each member receives the same share. In order to ensure fairness between members, the application of game theory on cooperative framework has been widely used – through the concept of Shapley value that is based on the estimation of the individual contribution of each player taken independently [21, 22].

Several studies already proposed two-stage methodology for the EC management. [2] worked on an iterative two-stage process that determines the internal community prices before minimizing the collective cost. Typical two-stage strategies rely on a real time adjustment of the control set-point that follows a look-ahead phase [23].

Based on the review provided above, we observe that there is a gap in the current literature with respect to both parts the operational phase and the sharing rule, as well as benefit perspectives from the overall community and individual levels. While there are already some studies regarding a two-stage approach

in the context of EC, there has not been one that combines the operational energy management and the energy allocation for each individual. This paper addresses this gap by a new two-stage decomposition that decouples in time the EMS and the allocation rules between members performed on a monthly basis (i.e., the billing period). Especially, various strategies are investigated for the two corresponding phases. At first, rule-based as well as optimization-based EMSs are implemented for the system operation. Secondly, the bill for each participant is computed on a monthly basis with regard to different strategies to contractually allocate the community generation to the different members (i.e., different computations of the KoR). Ultimately, there are different options in each stage which are expected to give freedom of choice for the EC. The decoupled approach allows to cover a wide range of preferences for different communities that may want to implement tailored distributions for the benefits sharing among members.

The main contributions of this paper are the following:

- A two-stage framework with the computation of the EMS, followed by the allocation rules for the community energy;
- A comparison of different options of EMS as well as KoR used by the community (forty different combinations);
- A model of penalty for storage power variations to avoid degradation;
- The discussion on the benefits brought by joining the EC in terms of bill reduction for the different options and the best proposition results, namely 11.7 % of collective saving and 11 to 19 % of individual savings.

The rest of this paper is organized as follows. Section 2 introduces the EC environment and describes the energy allocation concept as well as the bills computation (both individual and collective). Section 3 presents the proposed methodology, with a description of the different strategies envisioned for both the operational and settlement phases as well as a novel penalty model for the storage power variations. The use case is then described in Section 4 where results are analyzed in terms of energy efficiency and economic performances at both community and individual levels. Finally, Section 5 concludes this paper and provides points for future works.

2. System model

2.1. Energy community environment

An energy community is defined as an organization of several consumers or prosumers that may be equipped with local assets such as solar panels or energy storage systems. As illustrated in Figure 1, different stakeholders are identified within the EC context:

PMO: the legal entity that takes care of the community organization and communications with external parties. Among several duties, the main task of the PMO is to define the allocation rule of the local generation among all the members (i.e., KoR), which then affects individual bills [11].

Individual members: the customers/prosumers that are willing to join the community. Local generation is limited to solar photovoltaic (PV) while the storage system can consist of stationary (usually Li-ion) batteries and/or mobile electric vehicles (EV) with grid-to-vehicle and vehicle-to-grid charger capabilities.

DSO: the distribution system operator whose main task is to measure and validate the energy flows at the individual meters. Using the sharing rules provided by the PMO, the DSO then forwards the appropriate energy values to the suppliers for billing purposes.

Suppliers: the conventional energy providers, taking here the role of complementary suppliers in addition to the local energy – i.e., they supply any deficit and absorb any surplus of community energy.

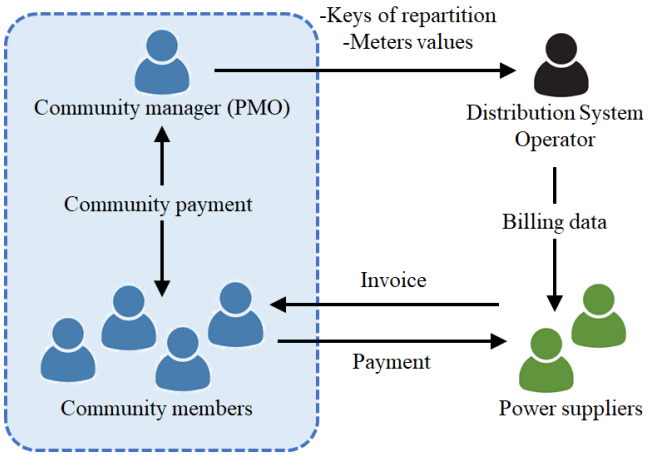

Figure 1: Different parties and their roles in the CSC framework.

Figure 2 displays a typical architecture for an energy community. In this paper, the EC is merely modeled as an energy hub in which grid constraints are not considered and the management lies only on the active power. The physical connection between participants exist through the public distribution grid, as usual. The flows shall then be subjected to grid usage taxes that are not considered here. The EC allows energy sharing through a virtual community hub. In this setting, $P_{n,t}^{gd^+}$ and $P_{n,t}^{gd^-}$ denote the power imported and exported from/to the public grid for a member n at a time t. These flows are subject to suppliers' rate for both import (electricity contract as usual) and export (feed-in tariff contract). Similarly, $P_{n,t}^{comm^+}$ and $P_{n,t}^{comm^-}$ refer to the power imported and exported from/to the community and represent the internal energy exchange between the community members. For both grid and community flows, the distinction is made between exported and imported energy, (1) and (2) respectively, as the flows may be subject to distinct tariffs based on their direction (i.e., purchase or sell).

$$P_{n,t}^{gd} = P_{n,t}^{gd^+} - P_{n,t}^{gd^-} \tag{1}$$

$$P_{n,t}^{comm} = P_{n,t}^{comm^+} - P_{n,t}^{comm^-} \tag{2}$$

From the perspective of the members and DSO, the only physical measurable quantity is the meter energy flow ($P_{n,t}^{meter}$)

which can then be contractually decomposed in two parts: 1) the grid power and 2) the power exchanged with the community, as expressed in (3). As further described, grid and community rates are different, which allows an arbitrage and optimization at the individual levels that ultimately impacts the whole community cost or revenue.

$$P^{meter}_{n,t} = P^{gd}_{n,t} + P^{comm}_{n,t} \tag{3}$$

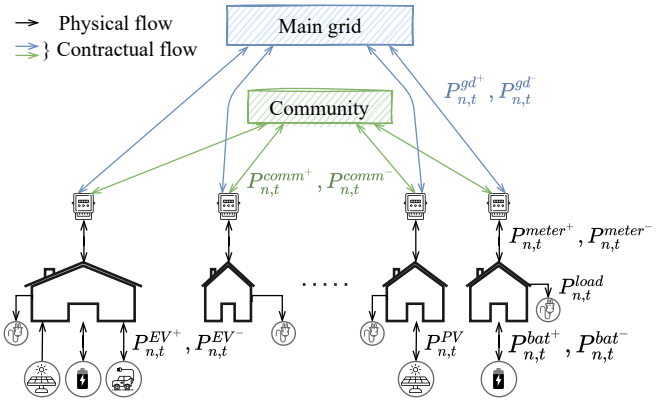

Figure 2: Typical energy community architecture.

2.2. *Energy allocation through the keys of repartition*

As there are many participants, the allocation rules of the whole community production are crucial in order to ensure minimum overall bill as well as fairness in the benefit sharing among the participants. In France, these allocation rules are known as the *keys of repartition* (KoR). Those coefficients ($\lambda_{n,t}$) define the amount of community generation that is allocated to each member. They naturally range from 0 to 100 % and are computed on a monthly basis with an half-hour resolution. The amount of community generation ($P^{prod}_{coll,t}$) is computed by summing the overall energy export at the individual meter level ($P^{meter^-}_{n,t}$) as in (4). The portion of the collective energy allocated to a given participant at a given time step ($P^{alloc}_{n,t}$) is then computed following (5). Obviously, the summation of the KoR for all members shall be less than or equal to 100 % as expressed in (6).

$$P^{prod}_{coll,t} = \sum_{n \in \mathcal{N}} P^{meter^-}_{n,t} \tag{4}$$

$$P^{alloc}_{n,t} = \lambda_{n,t} \times P^{prod}_{coll,t} \tag{5}$$

$$\sum_{n \in \mathcal{N}} \lambda_{n,t} \leq 100\% \tag{6}$$

The PMO is in charge of defining those KoR and forwards them to the DSO [11]. At each measurement time step (i.e., 30 min), the DSO computes the collective production and applies the KoR in order to obtain the allocated energy for each individual along with the residue that shall be paid to/by the supplier in case of deficit or excess of local generation.

Two types of KoR are traditionally considered: static or dynamic [24]. For the static one, the keys display the same predefined values at every time step along the month. On the contrary, dynamic keys display different values over time and allow for a customized allocation which ultimately impacts the way the benefit is shared among the community members.

As an example, the default KoR provided by the French DSO are based on the ratio of the participant's consumption relative to the overall community consumption at each measurement step (i.e., dynamic prorate consumption) [24]. However, it is possible to propose other strategies to compute those KoR based on the community preferences which leads to different value sharing between the participants.

It is worth mentioning that, particularly for static keys, the energy allocated to a member (at a given time step) may exceed the consumption, which may be contractually feasible but physically irrelevant. In order to tackle this issue, the individual power purchased from the community ($P^{comm^+}_{n,t}$) shall be the minimum value between the allocated power (from community) and the meter consumption power ($P^{meter^+}_{n,t}$) [24] ((7)). Then, if any, the deficit power that is still needed to be supplied by the upstream grid ($P^{gd^+}_{n,t}$) can be obtained following (8).

$$P^{comm^+}_{n,t} = \min\left(P^{alloc}_{n,t}; P^{meter^+}_{n,t}\right) \tag{7}$$

$$P^{gd^+}_{n,t} = P^{meter^+}_{n,t} - P^{comm^+}_{n,t} \tag{8}$$

Similarly, an additional concern arises in cases where the aggregated production at the community level is higher than the aggregated consumption. The challenge is then to define who will receive the credit for this surplus that is physically sold back to the main grid (at the feed-in tariff).

To determine the surplus, first we need to compute the overall collective self-consumption power at each time step ($P^{selfcons}_{coll,t}$) with (9). The collective surplus $P^{surplus}_{coll,t}$ is then defined as the difference between the aggregated net produced and self-consumed power [24] at every time step, in (10). It does not correspond to a physical quantity such as the difference between the aggregated net production and consumption. Instead, the surplus is computed from the energy allocated that was not self-consumed (i.e., if the energy allocated is higher than the consumption) and from the aggregated production that has not been allocated to anyone. The allocation rule of this collective surplus to each member has been regulated by the DSO following the ratio of the individual production to the overall community production at each time step, as in (11) [24], such that the individual surplus corresponds to the exported energy to the grid, $P^{gd^-}_{n,t}$. Ultimately, the amount of energy sold to the community $P^{comm^-}_{n,t}$ can be computed as the difference between the production measured at the meter $P^{meter^-}_{n,t}$ and the grid feed-in energy, as expressed in (12).

$$P^{selfcons}_{coll,t} = \sum_{n \in \mathcal{N}} P^{comm^+}_{n,t} \tag{9}$$

$$P^{surplus}_{coll,t} = P^{prod}_{coll,t} - P^{selfcons}_{coll,t} \tag{10}$$

$$P^{gd^-}_{n,t} = \frac{P^{meter^-}_{n,t}}{P^{prod}_{coll,t}} \times P^{surplus}_{coll,t} \tag{11}$$

$$P^{comm^-}_{n,t} = P^{meter^-}_{n,t} - P^{gd^-}_{n,t} \tag{12}$$

As an example, Table 1 displays different possibilities for the allocation rules applied to a community of three members

Table 1: An example of different strategies for the KoR at a given time step for an EC of three houses (H_1, H_2, H_3 are house 1, 2, and 3, respectively).

$\lambda_{n,t}$		$P^{alloc}_{n,t}(W)$		$P^{comm^+}_{n,t}(W)$		$P^{gd^+}_{n,t}(W)$		$P^{surplus}_{coll,t}$	$P^{gd^-}_{n,t}(W)$		$P^{comm^-}_{n,t}(W)$	
H_1	H_2	H_1	H_2	H_1	H_2	H_1	H_2	(W)	H_3	H_4	H_3	H_4
0.5	0.5	5	5	5	5	0	10	0	0	0	2	8
0.25	0.75	2.5	7.5	2.5	7.5	2.5	7.5	0	0	0	2	8
0.6	0.4	6	4	5	4	0	11	1	0.2	0.8	1.8	7.2

at a given time step – i.e., for the same physical flows at the meter level but with different KoRs. House H_3 and H_4 are the producers and the collective production is distributed between the houses H_1 and H_2 based on the KoR, with the meter values as follows:

- House H_1: 5 W
- House H_2: 15 W
- House H_3: -2 W
- House H_4: -8 W

There are three different investigated values for the KoR in Table 1. For the first setting, the community energy is equally shared and the house H_2 needs to import a substantial amount from the main grid. The next set of keys is the prorate consumption. The consumers get energy from the community according to the ratio of their consumption relatively to the aggregated load. For both sets of keys, all the community production is self-consumed locally and there is no surplus. However, for the last set of keys, the power allocated to house H_1 is higher than its consumption. Therefore, this energy which is not contractually self-consumed belongs to the collective surplus. House H_3 and H_4 then receive payback from the suppliers according to the allocation rules for the collective surplus.

The power measured in the household meters is the net flow of assets owned by each individual, which is controlled using an EMS. This paper provides four different options of EMS to manage the operational planning in an energy community. Subsequently, in order to share the community energy for every member, ten options of KoR strategy are presented such that a total of forty combinations will be investigated.

2.3. Individual and collective bill computation

As illustrated in the previous section, the KoR greatly affect the bill. Energy purchased or sold from/to the grid and the community are obviously subject to different prices as shown in (13) and (14). In order to incentivize users to join a community, the local buying price $\pi^{buy,comm}_n$ shall be lower than the grid rates (i.e., retail rates $\pi^{buy,gd}_n$). On the contrary, selling price in the community $\pi^{sell,comm}_n$ is generally higher than the grid feed-in-tariff $\pi^{sell,gd}_n$. The bill computation takes into account those prices with the time resolution $\Delta t = 30$ min.

$$B^{gd}_n = \Pi^{subs,gd}_n + \left(\pi^{buy,gd}_n \times \sum_{t\in\mathcal{T}} P^{gd^+}_{n,t} - \pi^{sell,gd}_n \times \sum_{t\in\mathcal{T}} P^{gd^-}_{n,t}\right) \times \Delta t \tag{13}$$

$$B^{comm}_n = \left(\pi^{buy,comm}_n \times \sum_{t\in\mathcal{T}} P^{comm^+}_{n,t} - \pi^{sell,comm}_n \times \sum_{t\in\mathcal{T}} P^{comm^-}_{n,t}\right) \times \Delta t \tag{14}$$

Participants in CSC receive then a monthly bill from the grid side (i.e., invoiced by the typical suppliers B^{gd}_n) and another bill from the community side (i.e., invoiced and managed by the PMO B^{comm}_n), as expressed in (15). The summation of the individual bill is the collective bill B_{coll}, expressed in (16), which will be used as an important parameter to determine the community welfare.

$$B_n = B^{gd}_n + B^{comm}_n \tag{15}$$

$$B_{coll} = \sum_{n\in\mathcal{N}} B_n \tag{16}$$

3. Two-stage methodology

The previous model equations are valid for any values of the meter flows profiles and any values of the keys of repartition. The physical meter flows in the models are affected by the considered EMS (Section 3.1) and the bill computation (at a monthly basis) that integrates the KoR (Section 3.2). The proposed methodology then relies on a two steps strategy that decouples the physical management of the community from the allocation mechanism, as presented in Figure 3. The first step consists in performing the community energy management and the second applies the allocation sharing rules between the members with the computation of the KoR on a monthly basis. Four different strategies for Stage 1 and ten different strategies for Stage 2 are investigated.

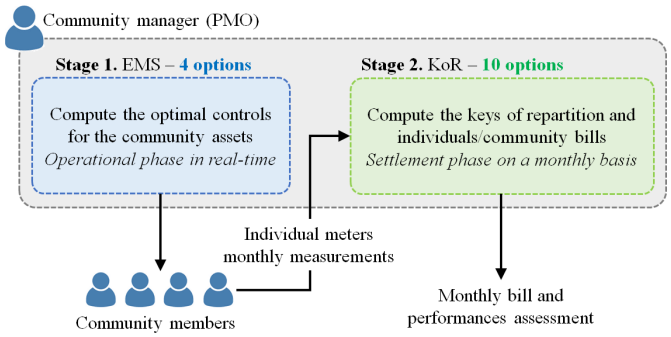

Figure 3: Framework of the proposed two-stage methodology.

In this paper, we deliberately separate the energy management from the energy allocation (i.e., through the KoR) in two

different stages. Hence, the keys of repartition (Stage 2) reflect the settlement of energy allocation for each member and are not necessarily related to the physical flows obtained from the energy management (Stage 1). In particular, this decoupled approach allows testing and comparing different methods for the EMS on one side, and for the KoR on the other, as different energy communities may have different goals and priorities in terms of benefit sharing.

3.1. Stage 1: Energy management strategy

This section describes the first stage of the proposed methodology. In regard of the overall community, this stage coordinates the energy system components in order to determine the net physical flows at the individual meters, that will be used further in Stage 2. Two rule-based and two optimization-based EMSs are investigated. All method options of EMS are centralized (i.e., performed in the community level) such that every member operates their assets according to the same EMS applied in the community. In practice, the EMS controls the storage (both battery and EV for the optimization-based EMSs and only battery for the rule-based EMSs) at every time step. It is important to note that in this paper, all the investigated management strategies are based on deterministic profiles for the load and generation and are performed in an offline mode. Especially, the operation is computed over a monthly horizon with a 30 min time resolution. In the operational phase, such EMS shall be implemented in the form of model predictive control and analyzed with regard to its robustness and ability to handle uncertainties. It is not the scope of this paper, which focuses on the performance's assessment of different strategies for a given topology of community.

3.1.1. Rule-based approaches

The rule-based approaches rely on a simple implementation that is a step-by-step decision process. We provide two options for the rule-based control: individual or community.

A. EMS_1: Individual rules. The first investigated rule-based control relies on individual decisions for each participant. For each time step, the local production (at the individual level) is self-consumed in priority. Then, any surplus is used to charge the battery, and lastly exported to the grid (in case the storage is full). Similarly, the grid import is the last resort in case of low local production and empty battery. The rules for each type of household are described in Algorithm 1. We differentiate the rules depending on the household assets and the procedure ultimately returns the power meter flow $P_{n,t}^{meter^+}$ that will be used further in Stage 2. This operation strategy has been common and conventional for home solar battery systems [25].

B. EMS_2: Community rules. Among few literature that employ rule-based EMS in an EC, a simple approach would be to always choose the cheapest energy source to buy (i.e. whether from the community or the main grid) [26]. A step-by-step EMS that reserves available energy in the battery initially for own individual uses before released to the community after a certain time is proposed to improve the self-consumption [16].

Algorithm 1: Individual rules.

Input: $P_{max,n}^{PV}, P_{max,n}^{bat}, P_{n,t}^{load}, P_{n,t}^{PV}$

if $P_{max,n}^{PV} = 0$ *(i.e., household with no PV, no battery)* **then**
  $P_{n,t}^{meter^+} = P_{n,t}^{gd^+} = P_{n,t}^{load}$
end
if $P_{max,n}^{PV} > 0$ ***and*** $P_{max,n}^{bat} = 0$ *(i.e., household with only PV)* **then**
  foreach $t \in \mathcal{T}$ **do**
    if $P_{n,t}^{load} > P_{n,t}^{PV}$ **then**
      (i.e., local generation deficit)
      $P_{n,t}^{meter^+} = P_{n,t}^{gd^+} = P_{n,t}^{load} - P_{n,t}^{PV}$
    else
      (i.e., local generation surplus)
      $P_{n,t}^{meter^-} = -P_{n,t}^{gd^-} = P_{n,t}^{load} - P_{n,t}^{PV}$
    end
  end
end
if $P_{max,n}^{PV} > 0$ ***and*** $P_{max,n}^{bat} > 0$ *(i.e., household with PV and battery)* **then**
  foreach $t \in \mathcal{T}$ **do**
    if $P_{n,t}^{load} > P_{n,t}^{PV}$ **then**
      (i.e., local generation deficit)
      $P_{n,t}^{bat^-} = P_{n,t}^{load}$ - $P_{n,t}^{PV}$, s.t. battery power and SoC limits
      if $P_{n,t}^{load} > P_{n,t}^{PV} + P_{n,t}^{bat^-}$ **then**
        $P_{n,t}^{meter^+} = P_{n,t}^{gd^+} = P_{n,t}^{load} - P_{n,t}^{PV} - P_{n,t}^{bat^-}$
      end
    else
      (i.e., local generation surplus)
      $P_{n,t}^{bat^+} = P_{n,t}^{PV} - P_{n,t}^{load}$ s.t. battery power and SoC limits
      if $P_{n,t}^{load} + P_{n,t}^{bat^+} > P_{n,t}^{PV}$ **then**
        $P_{n,t}^{meter^-} = P_{n,t}^{gd^-} = P_{n,t}^{PV} - P_{n,t}^{load} - P_{n,t}^{bat^+}$
      end
    end
  end
end

In this paper, the main characteristics of the community rules are that the community production is used solely for the battery charge while the battery discharge is purely for individual consumption. The second rule-based EMS is presented in Algorithm 2. There are two main steps: 1) perform the individual rules EMS and 2) add rules at the community level in order to adjust the storage controls based on the collective production. Thus, a second set of rules is applied to adapt the storage control at the member level, which ultimately updates the meter flows at every time step. The notation $\xi P_{n,t}^{bat^+}$ is the additional amount of battery charge from the community for an individual n at time step t. It is an iterative process to charge the neighbors' battery that continues until there is no more remaining

collective production to be shared or all batteries are full.

3.1.2. Optimization-based approaches

Unlike the rule-based EMSs that rely on the instantaneous decisions, optimization-based EMSs considered in this paper encompass the whole time-horizon in their formulation. In these approaches, the EMS is defined as a conventional optimization problem at the community level. The decision variables are the energy flows and assets controls for every individual n and at every time step t (i.e., the grid import and export $P^{gd^+}_{n,t}$, $P^{gd^-}_{n,t}$, the community import and export $P^{comm^+}_{n,t}$, $P^{comm^-}_{n,t}$, the storage charge and discharge $P^{st^+}_{n,t}$, $P^{st^-}_{n,t}$ which can be battery $P^{bat^+}_{n,t}$, $P^{bat^-}_{n,t}$, or EV $P^{EV^+}_{n,t}$, $P^{EV^-}_{n,t}$, the state of charge of storage $SOC^{st}_{n,t}$ which refers to both battery and EV, and the individual self-consumption power $P^{indsc}_{n,t}$). All those variables are positive semi-definite. This subsection describes the generic set of constraints that is considered to represent the system and its operation in the optimization-based EMSs. We do not include any binary variable but we always check at the end of the simulation that there is only one positive value or all zeros for these pairs $(P^{gd^+}_{n,t}, P^{gd^-}_{n,t})$; $(P^{comm^+}_{n,t}, P^{comm^-}_{n,t})$; $(P^{st^+}_{n,t}, P^{st^-}_{n,t})$.

The first set of constraints bounds the grid and community power flows. For each individual, the import and export power flows are limited by the subscribed power P^{subs}_n according to the contract with the supplier, as in (17) and (18). Also, we limit the individual peak power after joining the community by its initial peak load over the simulated period, as in (19), to avoid increased load levels.

$$P^{gd^+}_{n,t} + P^{comm^+}_{n,t} \leq P^{subs}_n \qquad \forall n \in \mathcal{N}, \forall t \in \mathcal{T} \tag{17}$$

$$P^{gd^-}_{n,t} + P^{comm^-}_{n,t} \leq P^{subs}_n \qquad \forall n \in \mathcal{N}, \forall t \in \mathcal{T} \tag{18}$$

$$\max\left(P^{gd^+}_{n,t}\right) \leq \max\left(P^{load}_{n,t}\right) \qquad \forall n \in \mathcal{N} \tag{19}$$

The second set of constraints is related to the storage operation. Maximum charge and discharge rate are ensured with (20) and the bounds of state of charge (SoC) with (21). The SoC computation accounts for charge and discharge efficiencies following (22). Besides, (23) and (24) set the SoC values at the beginning and the end of the simulated time horizon, respectively. They shall be equal for energy conservation purposes. There is no differentiation so far between the stationary storage (i.e., battery) and the mobile storage (i.e., EV). Unlike typical EV constraints, here we exclude the requirement of SoC level increment during the plug-in period, assuming the fuel charging can be performed outside the house, at the office building for example. This way, we try to only quantify EV's advantage as a storage (by storing energy to be used later in the house) and ignore its definitive drawbacks (charging requirement for transportation). However, we model the periodic unavailability of the EV, which will be explained later in Section 4.1.

$$0 \leq P^{st^+}_{n,t}, P^{st^-}_{n,t} \leq P^{st}_{max,n} \qquad \forall n \in \mathcal{N}, \forall t \in \mathcal{T} \tag{20}$$

$$SOC^{st}_{min,n} \leq SOC^{st}_{n,t} \leq SOC^{st}_{max,n} \qquad \forall n \in \mathcal{N}, \forall t \in \mathcal{T} \tag{21}$$

Algorithm 2: Community rules.

Input: $P^{load}_{n,t}, P^{PV}_{n,t}$

foreach $t \in \mathcal{T}$ **do**
  Run individual rules (Algorithm 1) with output: $P^{meter^+}_{n,t}, P^{meter^-}_{n,t}, P^{bat^+}_{n,t}, P^{bat^-}_{n,t}, SOC^{bat}_{n,t}$
  while $\left(P^{prod}_{coll,t} > 0\right)$ ***and*** $\exists n \in \mathcal{N}$, $\left(0 < P^{bat^+}_{n,t} < P^{bat}_{max,n}$ ***and*** $SOC^{bat}_{n,t} < 100\%\right)$ *(i.e., while there is still production and if exist a battery that is not fully charged)* **do**
    Additional charge from community to each consumer's battery: $\xi P^{bat^+}_{n,t} = \frac{SOC^{bat}_{max,n} - SOC^{bat}_{n,t}}{\sum_{n\in\mathcal{N}}\left(SOC^{bat}_{max,n} - SOC^{bat}_{n,t}\right)} \times P^{prod}_{coll,t}$ s.t. battery power and SoC limits $\left(\forall n \in \mathcal{N} | P^{meter^+}_{n,t} > 0\right)$
    $P^{bat^+}_{n,t} = P^{bat^+}_{n,t} + \xi P^{bat^+}_{n,t}$
    $SOC^{bat}_{n,t} = SOC^{bat}_{n,t} + \xi P^{bat^+}_{n,t} \times \mu^{bat}_n \times \Delta t \times \frac{100}{E^{st}_{max,n}}$
    $P^{meter^+}_{n,t} = P^{meter^+}_{n,t} + \xi P^{bat^+}_{n,t}$
    $P^{prod}_{coll,t} = P^{prod}_{coll,t} - \sum_{n\in\mathcal{N}} \xi P^{bat^+}_{n,t}$
  end
end

$$SOC^{st}_{n,t+1} = SOC^{st}_{n,t} + \left[P^{st^+}_{n,t} \times \mu^{st}_n - \frac{P^{st^-}_{n,t}}{\mu^{st}_n}\right] \times \Delta t \times \frac{100}{E^{st}_{max,n}} \qquad \forall n \in \mathcal{N}, \forall t \in \mathcal{T} \tag{22}$$

$$SOC^{st}_{n,1} = SOC^{init}_n \qquad \forall n \in \mathcal{N} \tag{23}$$

$$SOC^{st}_{n,end} \geq SOC^{init}_n \qquad \forall n \in \mathcal{N} \tag{24}$$

A set of constraints related to the overall individual generation and consumption is considered. The overall individual generation in (25) (i.e., the left part of the equation) is composed of the PV production $P^{PV}_{n,t}$ and the storage discharge $P^{bat^-}_{n,t}, P^{EV^-}_{n,t}$ and may be used for the individual self-consumption $P^{indsc}_{n,t}$ or the power exported to the grid $P^{gd^-}_{n,t}$ or the community $P^{comm^-}_{n,t}$ (i.e., the right part of the equation).

$$P^{PV}_{n,t} + P^{bat^-}_{n,t} + P^{EV^-}_{n,t} = P^{indsc}_{n,t} + P^{gd^-}_{n,t} + P^{comm^-}_{n,t} \qquad \forall n \in \mathcal{N}, \forall t \in \mathcal{T} \tag{25}$$

Next, the overall individual demand in (26) can be supplied by individual assets and/or imported from the grid and/or the community.

$$P^{load}_{n,t} + P^{bat^+}_{n,t} + P^{EV^+}_{n,t} = P^{indsc}_{n,t} + P^{gd^+}_{n,t} + P^{comm^+}_{n,t} \qquad \forall n \in \mathcal{N}, \forall t \in \mathcal{T} \tag{26}$$

At the community level, the overall power balance in (27) represents the equality of exchanged power (between import and export) while neglecting the losses in the local community network.

$$\sum_{n\in\mathcal{N}} P^{comm^+}_{n,t} = \sum_{n\in\mathcal{N}} P^{comm^-}_{n,t} \qquad \forall t \in \mathcal{T} \tag{27}$$

Finally, the net physical meter flow for each member that will be used later in Stage 2 is the summation of the grid and community power, as in (28).

$$P^{meter^+}_{n,t} - P^{meter^-}_{n,t} = P^{gd^+}_{n,t} - P^{gd^-}_{n,t} + P^{comm^+}_{n,t} - P^{comm^-}_{n,t} \quad (28)$$

A. EMS_3: Maximization of self-consumption ratio. The first objective targeted in the optimization-based EMS is to maximize the self-consumption ratio (SCR), defined as the portion of local production that is consumed locally as in (29) [9, 27]. In other words, the higher the SCR, the lower the energy exported outside of the local system (i.e., grid feed-in energy). Thus, the management problem is formulated following (30) with a minimization of the grid export and fulfilling the sets of constraints previously introduced.

$$SCR = 1 - \frac{\sum_{n\in\mathcal{N}}\sum_{t\in\mathcal{T}} P^{gd^-}_{n,t}}{\sum_{n\in\mathcal{N}}\sum_{t\in\mathcal{T}} P^{PV}_{n,t}} \quad (29)$$

$$f_1 = \textbf{min} \sum_{n\in\mathcal{N}}\sum_{t\in\mathcal{T}} P^{gd^-}_{n,t} \quad (30)$$

$$s.t.\ (17) - (28)$$

B. EMS_4: Maximization of self-sufficiency ratio. The other optimization-based EMS relies on the maximization of the self-sufficiency ratio (SSR) which is defined as the ratio of the consumption that is supplied by the local generation as shown in (31) [9, 27]. Implicitly, a maximum SSR corresponds to a minimum import from the upstream grid. Thus, the management problem is rewritten following (32).

$$SSR = 1 - \frac{\sum_{n\in\mathcal{N}}\sum_{t\in\mathcal{T}} P^{gd^+}_{n,t}}{\sum_{n\in\mathcal{N}}\sum_{t\in\mathcal{T}} P^{load}_{n,t}} \quad (31)$$

$$f_1 = \textbf{min} \sum_{n\in\mathcal{N}}\sum_{t\in\mathcal{T}} P^{gd^+}_{n,t} \quad (32)$$

$$s.t.\ (17) - (28)$$

C. Penalty for storage power variations. One contribution of the paper is the introduction of a storage penalty proposed to reduce its aging by avoiding very high peak power during both the charging and discharging phases. With the traditional model previously introduced, the main drawback is that the storage is merely considered as an energy reserve managed by the EMS. Ultimately, a same amount of provided energy over several time steps can correspond to a wide range of power profiles. As an example, from the optimization perspective, a discharge at 4 kW during half an hour would return the same performances (i.e., energy balance and bill) than a 1 kW discharge during two hours. However, the later incurs less degradation to the storage with lower C-rate [28]. Thus, the idea introduced here is to smooth the storage power profiles.

Mathematically, a penalty is introduced with the summation of storage power variations between two successive time steps. Those variations (upward and downward) are computed following (33) and (34) with the introduction of two additional semi-definite positive decision variables $\Delta P^{st^+}_t$ and $\Delta P^{st^-}_t$. The notation |...| represents the cardinal function (i.e., the number of elements in the set).

$$\Delta P^{st^+}_{n,t} - \Delta P^{st^-}_{n,t} = P^{st}_{n,t} - P^{st}_{n,t-1} \qquad \forall n \in \mathcal{N}, \forall t \in \mathcal{T} \quad (33)$$

$$\rho^{st}_n = \frac{\sum_{t\in\mathcal{T}}(\Delta P^{st^+}_{n,t} + \Delta P^{st^-}_{n,t})}{|\mathcal{T}| * P^{st}_{max,n}} \qquad \forall n \in \mathcal{N} \quad (34)$$

This penalty is ultimately introduced in the objective function of the first stage optimization-based approaches as in (35) but would not change the resulting objective value with a proper selection of the penalty factor α.

$$f'_1 = f_1 + \alpha \times \sum_{n\in\mathcal{N}} \rho^{st}_i \quad (35)$$

3.2. Stage 2: Keys of repartition and energy allocation

The second stage is run at a monthly billing interval after the energy management (Stage 1) has been completely performed previously. The direction of the load flow through the meter from Stage 1 denotes and differentiates the producers and the consumers at every time step. This section proposes ten different schemes to compute the KoR that will ultimately impact the bill computation as described in Section 2.2 and Section 2.3.

3.2.1. KoR_1: Identical

The first considered KoR are static with constant values over the successive time steps. As expressed in (36), those values can simply rely on an equal sharing among the community members $\mathcal{N}$. The ratio is always the same but the amount of allocated power is different depending on the collective production at each time step.

$$\lambda_{n,t} = \frac{1}{|\mathcal{N}|} \quad (36)$$

3.2.2. KoR_2: Prorate consumption

The second investigated keys refer to the base scheme proposed by the French DSO. The collective production in the community is distributed based on the amount of net load of each consumer at each time step relative to the total community demand ((37)).

$$\lambda_{n,t} = \frac{P^{meter^+}_{n,t}}{\sum_{n\in\mathcal{N}} P^{meter^+}_{n,t}} \quad (37)$$

3.2.3. KoR_3: Prorate production

The previous method may be counterproductive as it could encourage the members to increase their consumption in order to capture greater portions of the community generation. In order to favor the generation rather than the consumption, the next considered approach relies on a prorate of the generated energy of each individual over the total community production over a month (i.e., static KoR) as described in (38). Note that under this scheme, members with no local asset will not "receive" any energy from the community as they do not produce anything.

$$\lambda_{n,t} = \frac{\sum_{t\in\mathcal{T}} P^{meter^-}_{n,t}}{\sum_{n\in\mathcal{N}}\sum_{t\in\mathcal{T}} P^{meter^-}_{n,t}} \quad (38)$$

3.2.4. KoR_4: Prorate investment

Instead of a prorate of the generated energy, the next static strategy computes the keys based on the individual investment relative to the overall equipment cost in the community as in (39). The considered cost only applies to the stationary assets (i.e., neglecting EV) with a capital cost per kW installed for the PVs and per kWh capacity for the batteries.

$$\lambda_{n,t} = \frac{C_n^{inv}}{\sum_{n\in\mathcal{N}} C_n^{inv}} \tag{39}$$

3.2.5. KoR_5: Hybrid

The hybrid KoR consist of two successive steps: 1) static and identical keys for each consumer at each time step ((40)) and 2) prorate of the consumption energy ((41)) [29]. The detailed procedure is shown in Algorithm 3. This strategy allows a more even distribution than the KoR_2 (prorate consumption keys). It also encourages the consumers to lower their consumption to be able to be covered 100 % by the community at the first step of the computation of the keys.

$$\lambda_{n,t}^{h_1} = \frac{1}{|\{n \in \mathcal{N} | P_{n,t}^{meter^+} > 0\}|} \tag{40}$$

$$\lambda_{n,t}^{h_2} = \frac{P_{n,t}^{meter^+}}{\sum_{n\in\mathcal{N}} P_{n,t}^{meter^+}} \tag{41}$$

Algorithm 3: KoR_5: Hybrid.

Input: $P_{n,t}^{meter^+}$, $P_{n,t}^{meter^-}$, $\lambda_{n,t}^{h_1}$, $\lambda_{n,t}^{h_2}$

foreach $t \in \mathcal{T}$ **do**
- $P_{n,t}^{alloc_{h_1}} = \lambda_{n,t}^{h_1} \times P_{coll,t}^{prod}$;
- $P_{n,t}^{comm_{h_1}^+} = \min\left(P_{n,t}^{alloc_{h_1}}, P_{n,t}^{meter^+}\right)$;
- $P_{coll,t}^{selfcons} = \sum_{n\in\mathcal{N}} P_{n,t}^{comm^+}$
- Calculate remaining individual consumption to be fulfilled in Step 2: $P_{n,t}^{meter^+} = P_{n,t}^{meter^+} - P_{n,t}^{comm_{h_1}^+}$;
- Calculate remaining collective production to be shared in Step 2: $P_{coll,t}^{prod} = P_{coll,t}^{prod} - P_{coll,t}^{selfcons}$;
- $P_{n,t}^{alloc_{h_2}} = \lambda_{n,t} \times \sum_{n\in\mathcal{N}} P_{n,t}^{rem_{prod}}$;
- $P_{n,t}^{comm_{h_2}^+} = \min\left(P_{n,t}^{alloc_{h_2}}; P_{n,t}^{rem_{cons}}\right)$;
- $P_{n,t}^{comm_h^+} = P_{n,t}^{comm_{h_1}^+} + P_{n,t}^{comm_{h_2}^+}$;
- Next steps are (7) – (16) in Section 2 ;

end

3.2.6. KoR_6: Cascade

The cascade keys repeats the first step of the hybrid keys in an iterative manner [29]. Over several iterations, the remaining individual net consumption and the remaining collective production are updated. This process continues until all the collective production is allocated or all the net consumption is fulfilled (Algorithm 4). This method benefits the members with low and medium consumption because the allocated power at each iteration is equal for all members (i.e., members with low consumption are fully covered at first). Similar to the hybrid keys, the cascade formulation indirectly encourage the community members to lower their consumption if they want to be covered 100 % by the community local energy.

Algorithm 4: KoR_6: Cascade.

Input: $P_{n,t}^{meter^+}$, $P_{n,t}^{meter^-}$

foreach $t \in \mathcal{T}$ **do**
- $P_{coll,t}^{prod} = \sum_{n\in\mathcal{N}} P_{n,t}^{meter^-}$;
- $P_{coll,t}^{cons} = \sum_{n\in\mathcal{N}} P_{n,t}^{meter^+}$;
- Assign the initial consumption to a new parameter $P_{n,t}^{meter_0^+} = P_{n,t}^{meter^+}$;
- **while** $P_{coll,t}^{prod} > 0$ ***and*** $P_{coll,t}^{cons} > 0$ **do**
  - $P_{n,t}^{alloc} = \lambda_{n,t}^{h_1} \times P_{coll,t}^{prod}$;
  - $P_{n,t}^{comm^+} = \min\left(P_{n,t}^{alloc}, P_{n,t}^{meter^+}\right)$;
  - $P_{coll,t}^{selfcons} = \sum_{n\in\mathcal{N}} P_{n,t}^{comm^+}$;
  - Calculate remaining individual consumption to be fulfilled in the next iteration: $P_{n,t}^{meter^+} = P_{n,t}^{meter^+} - P_{n,t}^{comm^+}$;
  - Calculate remaining collective consumption: $P_{coll,t}^{cons} = \sum_{n\in\mathcal{N}} P_{n,t}^{meter^+}$;
  - Calculate remaining collective production to be shared in the next iteration: $P_{coll,t}^{prod} = P_{coll,t}^{prod} - P_{coll,t}^{selfcons}$;
- **end**
- $P_{n,t}^{gd^+} = P_{n,t}^{meter^+}$;
- $P_{n,t}^{comm^+} = P_{n,t}^{meter_0^+} - P_{n,t}^{meter^+}$;
- Next steps are (7)-(16) in Section 2;

end

3.2.7. KoR_7: Shapley value

The next considered method lies on the cooperative game theory concept with the computation of the Shapley value. This criterion is based on the marginal benefit brought by each member to the overall community. The main idea is that members who contribute more to the community shall be given higher rewards. In regard of the grand coalition defined by the set of all participants $\mathcal{N}$, let $\mathcal{S}$ be a subset of participants, defined as a coalition (i.e., a smaller community within the actual one).

In this paper, the benefit brought by each individual $v_t(S)$ is computed regarding the potential collective self-consumed energy at every time step (i.e., dynamic KoR) as expressed in (42) that depends on the considered coalition $\mathcal{S}$.

$$v_t(S) = \min\left(P_{coll,t}^{prod}, P_{coll,t}^{prod}\right) \tag{42}$$

The Shapley value is then the unique allocation rule in the cooperative game theory that divides value among members in such a way to satisfy various game-theory fairness criteria [30]. Mathematically expressed in (43), the Shapley value $\phi_{n,t}(\mathcal{N}, v_t)$

is the average of all marginal contributions of one household to each coalition it is a member of [31].

$$\phi_{n,t}(\mathcal{N}, v_t) = \sum_{\mathcal{S} \subseteq \mathcal{N} \setminus \{i\}} \frac{|\mathcal{S}|!\,(|\mathcal{N}| - |\mathcal{S}| - 1)!}{|\mathcal{N}|!} \left(v_t(\mathcal{S} \cup \{i\}) - v_t(\mathcal{S})\right) \tag{43}$$

The term $v_t(\mathcal{S} \cup \{i\}) - v_t(\mathcal{S})$ represents the marginal contribution of member i to a coalition $\mathcal{S}$. There are $|\mathcal{S}|!$ different ways the subset could be formed prior to the addition of member i and $(|\mathcal{N}| - |\mathcal{S}| - 1)!$ ways the remaining members could be added afterward. In order to have an average value, the sum of all possible sets of $\mathcal{S}$ is divided by the number of possible orders of the grand coalition $|\mathcal{N}|!$.

Note that, in some cases, this method does not return positive Shapley values for all members. Indeed, some members could contribute negatively or give a drag effect to the overall community benefit. Such cases are ignored while bounding the Shapley value to zero [32, 33]. The KoR are ultimately calculated following (44).

$$\lambda_{n,t} = \frac{\phi_{n,t}(\mathcal{N}, v_t)}{\sum_{n \in \mathcal{N}} \phi_{n,t}(\mathcal{N}, v_t)} \tag{44}$$

3.2.8. KoR_8: Minimization of collective bill

While all the previous methods rely on sets of rules and analytical formulations, additional strategies based on optimization are also investigated. The KoR $\lambda_{n,t}$ at each time step (i.e., a dynamic KoR) then becomes the decision variable to be optimized. The input parameters are the physical flows in the meters $P^{meter^+}_{n,t}$, $P^{meter^-}_{n,t}$ obtained from Stage 1 and the objective function is to minimize the collective bill (i.e., of all participants).

$$f_2 = \min \; B_{coll} \tag{45}$$

Keep in mind that different values for the keys incur different grid and community flows that ultimately impact the bill values (Section 2). As already mentioned, the total keys for all members at each time step must be less than or equal to 100 %, which is introduced as an additional constraint in this optimization problem in (6).

3.2.9. KoR_9: Equal bill saving ratios

The previous optimization maximizes the overall community welfare. However, one concern may arise in case the obtained results do not ensure fairness – i.e., some members may observe more benefits in terms of their individual bill reduction compared to the others.

Thus, an additional constraint is introduced to ensure that every member has the same bill reduction ratio compared to the baseline bill B^0_n – defined with regard to the individual meter flows and grid prices while excluding the purchase/sale from/to the community. An additional constraint is introduced in this optimization problem, in (46), to describe that each individual bill saving ratios (i.e., the left part of the equation) must be equal to the collective saving ratio (i.e., the right part of the equation).

$$\frac{B^0_n - B_n}{B^0_n} = \frac{\sum_{n \in \mathcal{N}} B^0_n - \sum_{n \in \mathcal{N}} B_n}{\sum_{n \in \mathcal{N}} B^0_n} \qquad \forall n \in \mathcal{N} \tag{46}$$

Figure 4: Geographical map of the community members: houses 1 – 7.

3.2.10. KoR_{10}: Maximization of the minimum individual savings

In the previous strategy, fulfilling the savings constraint may lead to a higher collective bill compared to the minimization of the overall cost (i.e., KoR_8). An approach to favor both collective and individual bill reduction is finally proposed. Instead of minimizing the collective bill, the idea here is to maximize the minimum individual bill reduction among all members as in (47). This way, we can obtain different bill savings among members but the range shall not be as wide as in the KoR_8 strategy and shall maintain the same minimum collective bill.

$$f_2 = \max \min \left\{ \frac{B^0_n - B_n}{B^0_n} \middle| \forall n \in \mathcal{N} \right\} \tag{47}$$

4. Results and discussion

4.1. Case study

An actual demonstrator located in the south of France and operated by the project industrial partner, Beoga, is considered as a case study. This demonstrator consists of seven households with the combination of solar PVs, batteries, and an EV car. It is presented in Figure 4.

Table 2 describes the installed capacities of each equipment with the EV power capacity referring to a fast-charging station installed in the community area. The reactive power flow is not considered in this study and the subscription power in kVA unit is equal to kW unit. The PV and battery installation cost are 1300 €/kW [34] and 1000 €/kWh [35], respectively – considered in the prorate investment allocation strategy (KoR_4).

Table 2: General parameters of each household.

House No.	PV (kW)	Bat (kW/ kWh)	EV (kW/ kWh)	Subs Power (kVA)	$\Pi_n^{subs,gd}$ (€/mo)	$\pi_n^{buy,gd}$ (c€/kWh)
1	3.2	5/9.8	11/40	6	8.4	12.97
2	6.12	5/9.8	-	36	24.96	13.31
3	-	5/9.8	-	6	8.4	12.97
4	3.2	-	-	9	10.05	13.31
5	3.2	-	-	9	10.05	13.31
6	3.2	-	-	6	8.4	12.97
7	-	-	-	9	10.05	13.31

The energy prices within the community need to be more appealing than the retail rates. The grid and community selling prices are then 6.5 c€/kWh and 7 c€/kWh, respectively. The community buying price is 7.5 c€/kWh while the grid buying price and the grid subscription fee (i.e., fixed price) are different for each member depending on their subscription power and retailer (Table 2).

Finally, the storage systems round trip efficiency is set at 95 %. The EV is available periodically with deterministic plug-in and plug-out times respectively: 6 p.m. and 8 a.m. on weekdays, 3 p.m. and 11 a.m. on Saturday, and 24 h plug-in on Sunday. The simulation is performed using a MATLAB optimization toolbox called YALMIP and a solver Gurobi, with one-month duration load and solar generation profiles obtained from local measurements in March 2021.

4.2. *Results for Stage 1*

In this section, we present and analyze the EMS results with the four investigated strategies. Figure 5 displays the results in terms of accumulated energy imported/exported from/to the grid and the community for one month of simulations. Note that the only physical power flow is in the house meter while the grid and community flow are rather contractual.

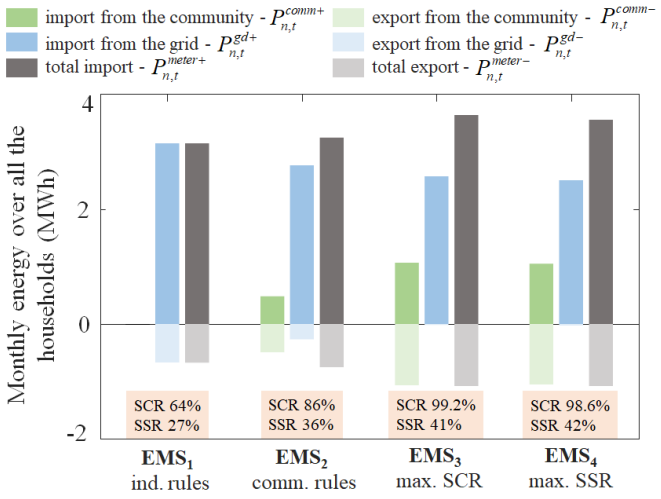

Figure 5: Energy import and export, SCR and SSR at the community level for one month simulation for different EMSs.

There is no community exchange in the individual rule-based EMS_1 as each house only manages energy individually. In the community rule-based EMS_2, the individual exported energy can be used solely to charge the neighbors' battery and not to supply the household electricity consumption. The grid imported and exported energy for EMS_2 are lower than the individual rules as there are energy exchange between neighbors. The optimization-based EMSs both lead to greater total import and export energy that consist in higher exchanges within the community and lower main grid exchanges compared to the rule-based ones. Besides, no feed-in energy to the grid has been observed using EMS_3 and EMS_4 which implies that the self-produced energy is utilized only for the local consumption within the community.

Figure 5 also displays the SCR and SSR for each energy management model. Similar to the value of energy exchange, the optimization-based EMSs allow reaching greater value of SCR and SSR. With almost 100 % SCR, most of the community generation is consumed locally. When controlling energy individually (i.e., individual rule-based EMS), the lowest level of SCR and SSR are observed due to the impossibility to capture energy exchanges between houses in that case.

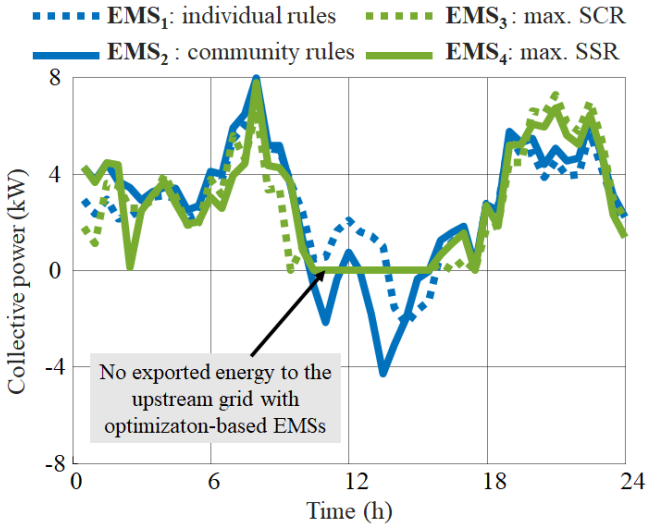

Figure 6: Physical power flow observed at the measurement meter at the community level at a sample day for different EMSs.

Figure 6 shows the net power flow at the community level

Table 3: Collective bill (€) with different energy management strategy (EMS) and keys of repartition (KoR)

	baseline	KoR_1	KoR_2	KoR_3	KoR_4	KoR_5	KoR_6	KoR_7	KoR_8	KoR_9	KoR_{10}
EMS_1	538	522	509	535	529	510	510	521	509	532	512
EMS_2	549	525	507	541	529	507	507	531	507	537	507
EMS_3	579	545	509	561	552	509	509	552	509	534	510
EMS_4	563	530	**497**	546	537	**497**	**497**	536	**497**	519	**497**

with positive values denoting a physical import from the upstream grid. It is worth noticing that the optimization-based approaches avoid any surplus injected back to the upstream grid (for the selected day), which explains the greater SCR.

The evaluation of the storage penalty model is shown in Figure 7. The battery profile without the power variations penalty shows several peaks. Using the proposed storage penalty, as described in Section 10, a flatter profile is achieved while keeping the same amount of charged and discharged energy (e.g., in the beginning period, the discharged energy remains 3.8 kWh). With an appropriate tuning of the penalty coefficient for the storage power variation α, the objective value remains unchanged.

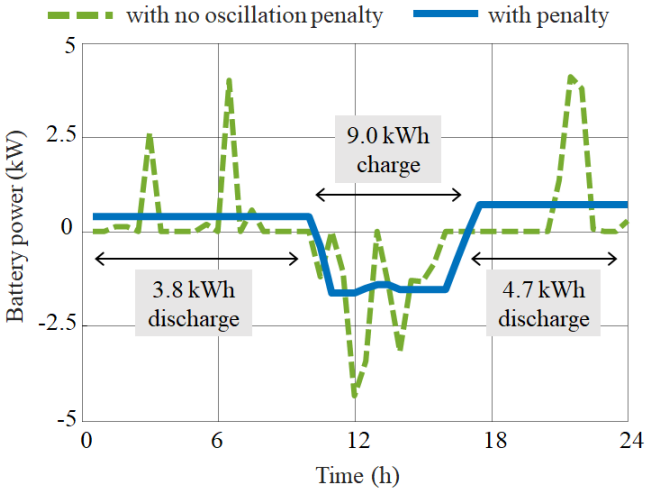

Figure 7: Battery power profile with and without the penalty model at a sample day using the energy management strategy EMS_4 that maximizes SSR.

4.3. Results of Stage 2

The EMS approaches in Stage 1 are run over a month in an off-line mode with deterministic profiles. Ultimately, it returns the controls for the community assets (i.e., the storage systems) along with the time-series profiles of all house power meter flows. Using different EMSs and KoRs, the result of collective bill (i.e., the summation of all individual bills) is shown in Table 3 for a total of forty different combinations. The baseline is computed with the physical power meter flows from the EMS and individual bills considering the grid prices only (i.e., no community and energy exchanges). Thus, the baseline bill displays different values depending on the considered EMS – the minimum collective cost is 538 €, obtained with the rule-based individual EMS_1. One important point to notice is that organizing a community leads to a reduced community bill in every investigated scenario for the KoRs. The ultimate lowest monthly cost of 497 € corresponds to 11.7 % of global improvement compared to the baseline EMS that maximizes the self-sufficiency (EMS_4).

The minimum collective cost for this EMS_4 is obtained with different strategies for Stage 2: best results are achieved using the default keys with KoR_2 prorate consumption (i.e., ratio of individual consumption over total community consumption), KoR_5 hybrid (i.e., at each time step, firstly identical allocation for consumers and secondly KoR_2 prorate consumption), KoR_6 cascade (i.e., iteration of identical allocation for consumers at each time step until no more production or no more consumption in the community), KoR_8 minimization of collective bill (i.e., embed the keys in an optimization problem with the objective to minimize the bill), and KoR_{10} maximization of the minimum individual saving (i.e., another optimization problem but with different objective that maximizes the minimum saving).

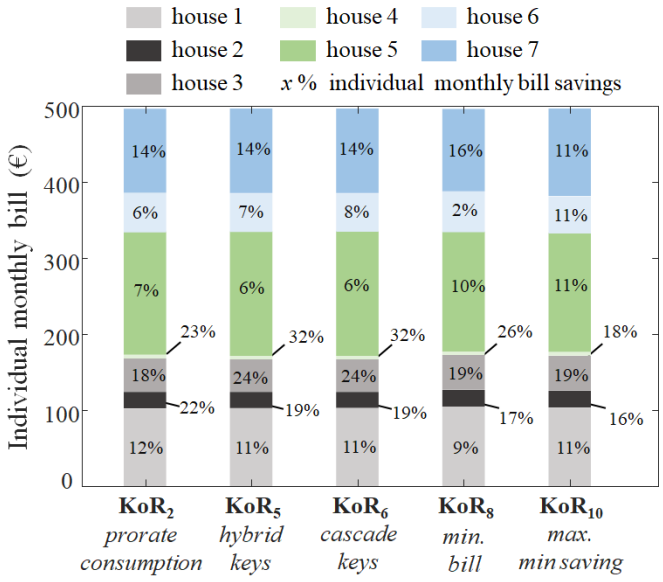

Figure 8: Individual bills and the reduction for strategies of KoR using the energy management strategy EMS_4 that maximizes SSR relative to the baseline.

However, the same collective bill corresponds to different combinations of individual bills and individual bill reductions depending on the considered method for Stage 2. Figure 8 displays the individual bills and saving ratios for the five strategies previously mentioned. Indeed, most strategies display a

wide range of individual bill reductions for different participants, from only 2 % up to 32 %. The proposed strategy based on the optimization of the minimal individual bill reduction (KoR_{10}) returns by far the best results in terms of fairness and uniform savings with individual bill reduction values between 11 % and 19 % compared to the base case. Obviously, this "saving standardization" incurs lower reduction for some participants (i.e., houses 1, 5, 6 and 7) and higher for others (i.e., houses 3 and 4).

With different values for the KoR, those five investigated strategies lead to various amount of energy allocated to the different members that alters their self-consumed energy along the simulated month, as displayed in Figure 9. Using hybrid and cascade strategy (KoR_5 and KoR_6), we can see that greater amounts of energy are allocated to small consumers (i.e., houses 2, 4 and 6). On the contrary, the collective self-consumed energy for big consumers (i.e., houses 1, 3, 5, and 7) are lower using the hybrid and cascade keys rather than the default keys proposed by the DSO (i.e., KoR_2).

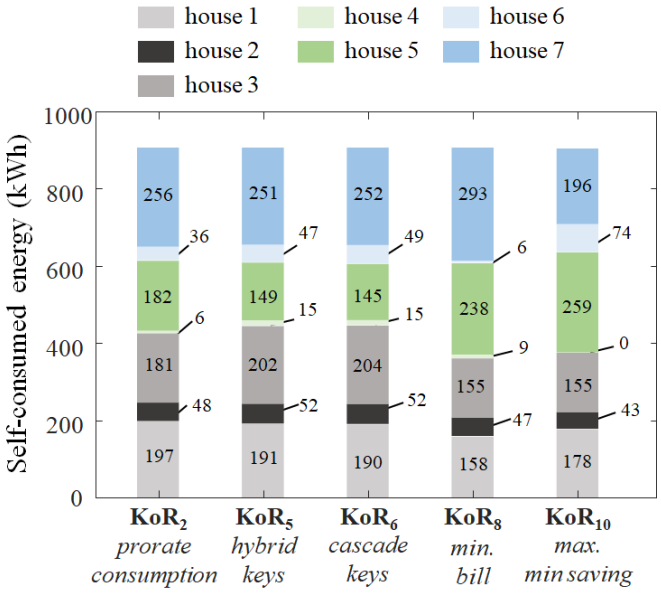

Figure 9: Self-consumed energy from the community at the individual level using the energy management strategy EMS_4 that maximizes SSR.

Finally, Figure 10 shows the energy exchanges on a given day with two different methods to compute the KoR: the default KoR_2 based on the ratio of consumption (Figure 10a) and the proposed KoR_{10} that maximizes the minimum saving (Figure 10b). At every time step, the positive values denote the share of community energy between the different consumers $P^{comm^+}_{n,t}$. The negative values display the contribution of each producer, which is obviously the same no matter the method computing the KoR (i.e., the physical export obtained after Stage 1 if there is no surplus exported to the upstream grid).

The keys that allocate the collective energy based on the individual consumption (KoR_2) always allocate a significant power to house 7 at all times as it is one of the biggest energy consumer. However, with the optimized keys KoR_{10}, in the beginning and end of the presented day, the community generation is allocated only to house 5 and 6. The power exported to the community is always equal to the power imported (i.e., power balance at the community level). The collective production is mostly provided by house 2 and house 1 since only these two houses have both PV and storage systems.

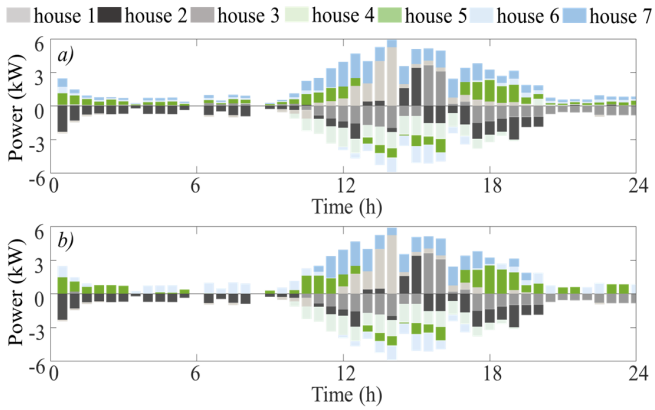

Figure 10: Power exchanged in the community for a sample day using the energy management strategy EMS_4 that maximizes the SSR and two strategies of KoR: a) KoR_2 prorate consumption and b) KoR_{10} maximization of the minimum individual saving ratios.

5. Conclusion

The methodology presented in this paper provides diverse options for the management and the profit allocation within an energy community performing collective self-consumption. The advantage of the two-stage strategy is to decouple the bill computation from the asset management at the community level. As observed, different strategies to allocate the energy among the members lead to different benefits in terms of bill reduction. It was shown from the results that CSC framework enables significant economic benefits at the community level as well as at the individual level. By forming a community, the case study of seven houses saves 11.7 % collectively and 11 to 19 % individually. This is considered as a huge improvement when compared to a baseline in which each household acts individually.

This study then provides valuable guidelines for community managers and participants to determine the most appropriate management and energy allocation strategies. We investigate four options of EMS and ten options of KoR for a total of forty different combinations. For the considered use case, the most satisfying results were obtained with an EMS that maximizes the self-sufficiency (EMS_4) and an allocation rule that tends to standardize the individual bill reduction (KoR_{10}). While the paper adopts French regulation as the framework, the resulting optimal method for EMS and KoR are generic and widely applicable to other contexts of energy communities. The decoupled mechanism in the two-stage methodology is important from the energy sharing perspective. It can be applied to any energy community in the settlement phase, in order to tune the

benefit sharing accordingly to preferences for customized distribution of the savings.

Further work will investigate the EMS implementation on the demonstrator. Indeed, the optimization were run in an offline mode with deterministic profiles over a month for performance assessment purposes. Especially in an actual deployment, uncertainties will have to be accounted for in the EMS. A comparison of the centralized EMS in this paper with a decentralized method is an interesting subject for the future research. Other works will focus on long-term planning in order to determine the most appropriate assets size or community configurations (e.g., numbers, types of users among other). Finally, the provision of ancillary services to the grid at the community level can be investigated in order to take advantage of an additional stream of revenues.

CRediT author contribution statement

Alyssa Diva Mustika: Conceptualization, Methodology, Software, Validation, Visualization, Writing- Original Draft. **Rémy Rigo-Mariani:** Conceptualization, Methodology, Writing-Reviewing and Editing. **Vincent Debusschere:** Supervision, Writing- Reviewing and Editing. **Amaury Pachurka:** Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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