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Abstract

With the widespread development of renewable energy sources, collective self-consumption (CSC) has been increasingly considered over recent years to sell the surplus of generated power to nearby consumers. However, appropriate energy allocation rules must be designed to efficiently share the energy among consumers. This paper aims to study two kinds of repartition keys for a CSC operation with multiple producers in the framework of an industrial multi-energy microgrid located in France. The default key considered in French regulations is compared to an optimized key based on the maximization of the income for the producers, in such a way as to maximize profitability by allocating the energy according to the consumers' electricity purchase price. The simulation results show that a CSC with an optimized key decreases the total electricity bill by 11.7%. For some producers, a reduction in the payback period between 6 months and 5 years is observed, compared to the case without CSC. A sensitivity analysis on economic assumptions is also proposed. The results show that the grid use tariff exemption is a key lever and makes it possible to find a more profitable selling price for producers and consumers, and to significantly reduce the payback period for investors.

Keywords

Microgrid, Collective self-consumption, energy sharing, energy communities, governance

1. Introduction

In recent years, renewable energy sources such as solar photovoltaic (PV) panels and wind turbines have been widely integrated into the energy mix. This major evolution implies the need to efficiently manage the excess power generated from these non-dispatchable sources. Most of the time, the power generated by renewable energy sources is in priority self-consumed by the producer (individual self-consumption). However, a surplus may remain if the producer's demand is lower than production. This excess energy can be stored in batteries, but

this solution is often too expensive in terms of investment and replacement costs (IRENA, 2020). As an alternative, the surplus can be sold to the main grid or to nearby consumers. The aggregation of geographically close producers and consumers exchanging energy is often referred to as an energy community (Frieden et al., 2019). It can be noted that the participants with a role of both producer and consumer are sometimes referred to in the literature as prosumers (Inês et al., 2020). Participatory, voluntary and open functioning is also put forward as a foundation of the concept of an energy community (Walker and Devine-Wright, 2008). Depending on the country and the regulations in force, an energy community is legally defined according to specific terms such as a "renewable energy community" (REC), "citizen energy community" (CEC) or "collective self-consumption" (CSC) (Frieden et al., 2019). Even if sharing energy between participants is common, some distinctions exist. As described in (Frieden et al., 2019), these concern the organizational and market aspects, the geographical extent, the location on the grid (voltage level), the status of the participants (companies, houses, local authorities, etc.), the governance and activities included in the operation management (generation, distribution, transport, etc.). The regulations in force in some European countries have been reviewed in several recent publications (Alaton et al., 2020; Frieden et al., 2021; Inês et al., 2020; Lormeteau, 2022). Most energy communities developed over the last few years were located in these countries, thanks to regulation recommendations and incentive directives established by the European Union (European Union, 2019, 2018). It should be emphasized that community-based markets differ from peer-to-peer markets, which are more linked to decentralized structures (Sousa et al., 2019, p.). The different kinds of local energy markets have been compared in a recent publication (Capper et al., 2022), including a comparison between energy communities, peer-to-peer and transactive energy markets.

One of the key points governing the operation of energy communities is the distribution of the energy generated and sold by the producers to the consumers, which is the responsibility of the legal entity managing the community (the energy community manager) (Frieden et al., 2021). This central entity communicates the allocation of energy to the distribution system operator (DSO) for billing purposes. Most of the time, the energy allocation is carried out in a settlement phase after the physical delivery of the energy. It is thus separated from the real-time control of the system. The financial balance of each participant and of the community depends on the rules taken into account for energy allocation. A literature review concerning energy allocation in energy communities shows that several methods and criteria can be considered (Gjorgievski et al., 2021). Among the possibilities, an energy criterion is often considered in the allotment rules. For example, self-sufficiency is maximized in the study proposed in (Reis et al., 2021), and in (Coignard et al., 2020), in which it is favoured by the integration of a demand-side management program and batteries. The self-consumption rate, which

represents the capability to use onsite the energy generated within a community, can also be considered, to use the generated energy as locally as possible (Viti et al., 2020). Energy can be allocated according to prorate rules, thanks to static or dynamic coefficients, as investigated in (Fina et al., 2022) where the authors considered a distribution in proportion to the consumers' demand. Even if an energy community should be driven by environmental values rather than financial profits, the economic balance must be taken into account in the energy allocation rules, to ensure the operation's profitability especially for the participants who invest in the means of production (Frieden et al., 2019). Therefore, the state-of-the-art shows that several studies have focused on the integration of an economic objective in the energy allocation step. Minimization of the electricity bills of participants (de Villena et al., 2022) or the overall cost at the level of the community (Cosic et al., 2021; Reis et al., 2022a) can be considered. In (Contreras-Ocaña et al., 2021), the energy is allocated in a fair way, to ensure that all participants obtained similar savings. The fairness is also considered in (Gjorgievski et al., 2022), with an allocation minimizing inequality between participants. The social welfare is maximized in the optimization proposed in (Perger et al., 2021), including the participants' willingness-to-pay. It should be noted that some concepts can be found in the literature, such as the game theory concept (Abada et al., 2020a, 2020b; Pilz and Al-Fagih, 2019) and the blockchain concept (Menniti et al., 2020; Van Cutsem et al., 2020). Finally, societal aspects are a category of criteria. The users' preferences are considered in (Stephant et al., 2021), with a multi-criteria approach including comfort, origin of electricity and costs. In (Reis et al., 2021), the goals pursued by the members are integrated in a multi-agent framework, considering cost minimization and comfort satisfaction for the consumers participating in a demand-side management program. Whatever the objective, the performances of an energy community depend on the characteristics of the participants, especially of their demand. The heterogeneity between actors has been investigated in (Reis et al., 2022b). Moreover, the study presented in (Fina et al., 2019) shows the influence of the kinds of buildings included in an energy community. It can be noted that an energy community can also concern participants located in the same residential building (Canova et al., 2022). Furthermore, the flexibility of the governance and of the energy allocation rules has to be ensured, in case there is an entry or withdrawal from the CSC operation, as investigated in (Mustika et al., 2022a; Perger and Auer, 2022). Demand-side management can also be found in the literature, allowing flexibility on load demand (Li et al., 2022, 2021).

This literature survey shows that most existing publications about energy allocation in the energy communities have considered a minimization of electricity bills and/or a maximization of self-consumption and self-sufficiency. The repartition in a way to foster investment profitability is less considered, which may not

encourage the development of such projects as the investment costs of means of production and storage can be high. It seems relevant to take profitability into account in the energy allocation rules in order to obtain a payback period that is acceptable to investors. Moreover, existing studies have focused on residential application frameworks. The literature lacks studies dealing with industrial application frameworks and multi-energy microgrids that could be beneficial for companies, whose load demand often occurs during the day, i.e. when PV panels produce energy. The growth of hydrogen needs for transport also implies that hydrogen must be produced every day, if possible from low-carbon sources. Thus, it could be beneficial to integrate a hydrogen producer into an energy community, to maximize the use of locally generated electricity. From these observations, this paper proposes an adapted energy allocation scheme for an energy community composed of industries and a hydrogen producer. The case study examined is a French seaport area, studied in a national French project called ESTUAIRE (Pole Mer Bretagne Atlantique, 2021). The development of a seaport microgrid is investigated. Thus, the regulations currently in force in France are considered. The regulatory framework suited to the case study presented corresponds to a so-called collective self-consumption operation set out under French regulations (French Government, 2017), in which the energy allocation rules are defined by a repartition key. It should be noted that several recent publications have studied the French context, especially the design of repartition keys (Mustika et al., 2022b), for example in proportion to consumption and according to a competitive exchange policy (Albouys-Perrois et al., 2022). In this paper, we propose to compare the default allocation rules considered in the regulation in force with an optimized allocation scheme favouring the income for the producers. Even if the case study is located in a specific country, the developments can be adapted to other countries with similar regulations (Frieden et al., 2021). It can be noted that the method is applicable for grid-connected microgrids and that the case of isolated microgrids refers to another regulatory framework (energy community with only local producers, without any external supplier). The main contributions of this paper are the following:

- The design of an optimized repartition key for a CSC operation, based on an income maximization for producers, thus a maximization of profitability and a minimization of the payback period;
- The study of the benefits brought by a CSC operation in an industrial multi-energies microgrid, with consumption occurring mainly when production exists (unlike CSC operations with residential buildings);

- A sensitivity analysis of the economic assumptions, to show how the results are influenced by the choice of the local energy price and by the network use tariff, considering a total or partial exemption of the latter.

This paper is organized as follows. Section 2 presents the studied fictitious CSC operation. In Section 3, the repartition keys defining the energy allocation rules are explained, as well as the calculations related to the financial assessment. Section 4 aims to compare the results obtained for several scenarios, and then a sensitivity analysis is carried out on economic assumptions. Finally, a conclusion and perspectives for future work are given in Section 5.

2. Description of the studied CSC operation

The fictitious CSC operation considered in this paper is an industrial multi-energy microgrid, the power flow scheme of which is presented in Fig. 1. This microgrid involves N_p = 12 participants, assuming that a participant corresponds to a building connected to the distribution network, which has its own electricity bill with a tariff contracted with an electricity supplier. The set of participants is denoted as $\mathcal{I} = \{1, \dots, N_p\}$. Six of these participants are energy producers as they own PV panels. All the participants have electrical loads and thus behave like a consumer. The participant 12 produces hydrogen to supply hydrogen loads (for mobility use), for which more details were given in a previous study (Roy et al., 2021). The integration of a hydrogen producer in a CSC operation allows the production of low-carbon hydrogen because it could benefit from the surplus of energy generated by the producers. This microgrid is connected to the main grid, which ensures that the load demand can be met whatever the local production level. Moreover, the main grid can absorb the surplus of generated power not consumed within the microgrid.

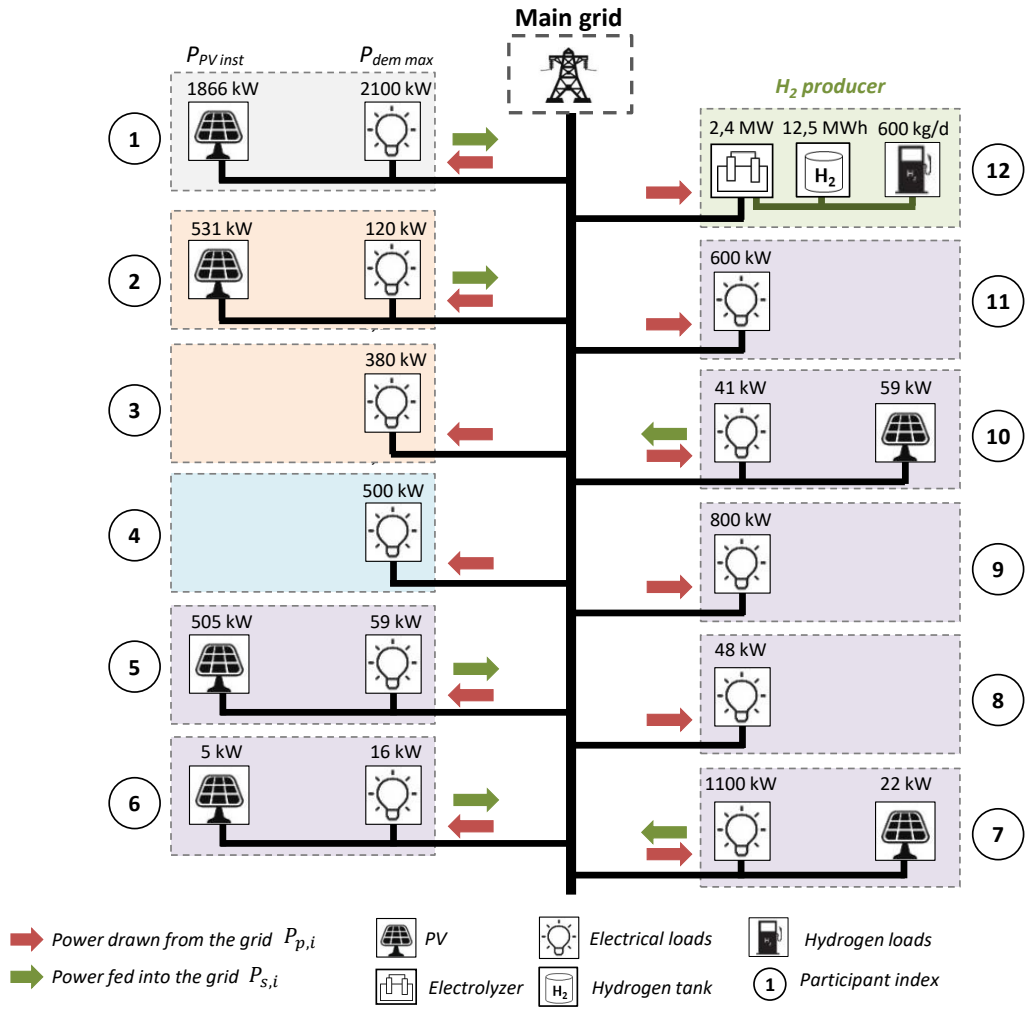

Fig. 1. Layout of the industrial microgrid of the considered CSC operation

In this study, it was assumed that the individual self-consumption of the power generated by PV is prioritized as much as possible, as that is the most profitable solution of energy valorisation. Indeed, according to the electricity tariffs of the case study, it is more beneficial for producers to use their generated power to supply their own demand, as the electricity purchase price (i.e. the price defining the electricity bill savings) is higher than the price of a sale to the grid, regardless of the buyer (the main grid or other participants). To simplify the study and the analysis of the results, the storage of energy in batteries is not considered (the installation of batteries can lead to an increase of the producers' payback period due to expensive investment costs). For each participant i, the power denoted as $P_{p,i}$ [kW] corresponds to the power purchased or drawn from the electrical grid, thus for a producer the lack of power after having considered the individual use of the power generated behind-the-meter. This power can also be called net consumption (de Villena et al., 2022). The power $P_{s,i}$ is that sold or fed into the electrical grid by the participant i, i.e. the surplus of generated power remaining after individual self-consumption (also called net production). These powers are considered as positive. They correspond to the

power measured by metering devices installed on the buildings of the community members, considering a time step of 30 min, as stated by the French regulation (ENEDIS, 2019). From the meaning of these powers, it must be noted that at any time a participant i is either a producer or a consumer, resulting in $P_{p,i} \times P_{s,i} = 0$. These powers will be used in Section 3 as input data of the CSC management algorithm, so as to share the power generated by the producers that is not used by individual self-consumption.

3. Design of energy allocation rules for the collective self-consumption operation

A CSC operation implies the establishment of energy allocation rules to define how the power surplus generated will be shared between consumers. This step consists of an *a posteriori* allotment of the energy in a settlement phase at the end of each month. It does not necessarily represent the physical exchanges occurring in the system and it is not dedicated to be assessed in real-time. It corresponds to a financial assessment step, performed after the delivery of electricity and is managed by a moral organizer (i.e. a legal entity or a legal person), for example the "*personne morale organisatrice*" (PMO) in France (French Government, 2017).

A scheme of the CSC operation structure considered is shown in Fig. 2, representing the data exchanged between entities about power allocation and billing. The power supplier represents the entity from which the participant purchases energy in the case of lack of power in the community (i.e. power drawn from main grid in Fig. 1). The power supplier may be different depending on the participant. The purchaser of surplus represents the entity which purchases the surplus of energy not consumed by the CSC consumers (i.e. power fed into the main grid). Before the start of the CSC operation, the moral organizer has to transmit to the DSO the energy sharing rules contracted between the participants gathered under the term of repartition key. As stated by the regulations (French Government, 2017), this repartition key can be based on default rules which consist of a power allocation proportional to the consumption of the participants. Alternatively, it can follow personalized rules. In the following part, a methodology is proposed for both kinds of repartition key, considering an optimized allocation allowing the producers income to be maximized for the second one.

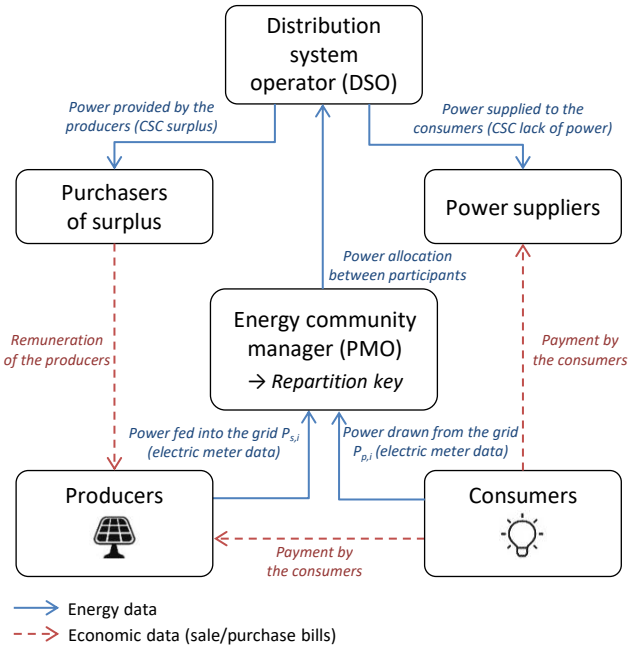

Fig. 2. Scheme of energy and economic data flows between the entities of the CSC operation considered, according to French regulations

3.1. *Proposed energy allocation rules*

To calculate the share of energy exchanged in the community, the powers $P_{p,i}$ and $P_{s,i}$ of participants introduced in Section 2 are split into two terms. One is related to the flow with the other participants (denoted as "local" by an index l) and the other corresponds to the flow with the main grid (denoted as "main" by an index m), such that for a participant i.

$$P_{p,i} = P_{p,l,i} + P_{p,m,i} \quad (1)$$

$$P_{s,i} = P_{s,l,i} + P_{s,m,i} \quad (2)$$

where $P_{p,l,i}$ [kW] is the power requested by participant i from the other CSC members, $P_{p,m,i}$ [kW] the power requested by participant i from the main grid (i.e. the supplier of electricity not provided by local sources), $P_{s,l,i}$ [kW] the power guaranteed by participant i to the other CSC members and $P_{s,m,i}$ [kW] the power guaranteed by participant i to the main grid (i.e. to the purchaser of surplus). These four powers are considered to be positive. Also, these powers are virtual and do not correspond to physical flows. They correspond to an *a posteriori* energy allocation for billing purposes only. An example of this power distribution is proposed in Fig. 3 for a small CSC operation, with the allocation of the power fed into and drawn from the grid by participant 1. For the power allocated within the CSC operation, an individual-to-individual allocation is considered, with $P_{p,l,i,j}$

representing the power requested by participant i from participant j, which is equal to $P_{s,l,j,i}$ representing the power guaranteed by participant j to participant i. This individual allocation must ensure that the following equations are met:

$$P_{p,l,i} = \sum_{j=1,j\neq i}^{N_p} P_{p,l,i,j} = \sum_{k=1,k\neq i}^{N_p} P_{s,l,k,i} \quad (3)$$

$$P_{s,l,i} = \sum_{j=1,j\neq i}^{N_p} P_{s,l,i,j} = \sum_{k=1,k\neq i}^{N_p} P_{p,l,k,i} \quad (4)$$

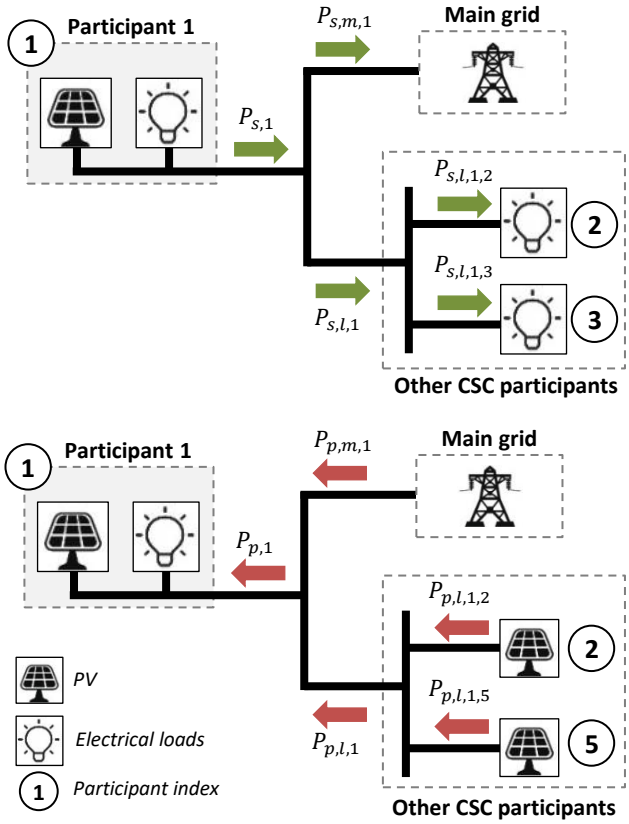

Fig. 3. Distribution of the power flows related to participant 1 for a case in which participant 1 sells energy (top scheme) and a case in which participant 1 purchases energy (bottom scheme)

The following sections present the calculation of these four virtual powers, according to the flowchart presented in Fig. 4. Firstly, the power fed into the main grid and into the CSC operation is calculated to evaluate the amount of power that can be exchanged within the community. Then, the generated power guaranteed to the CSC is allocated between consumers thanks to a repartition key, to determine the purchase from the CSC by each consumer. Finally, the individual-to-individual allocation is calculated, before deducing the remaining power requested from the main grid.

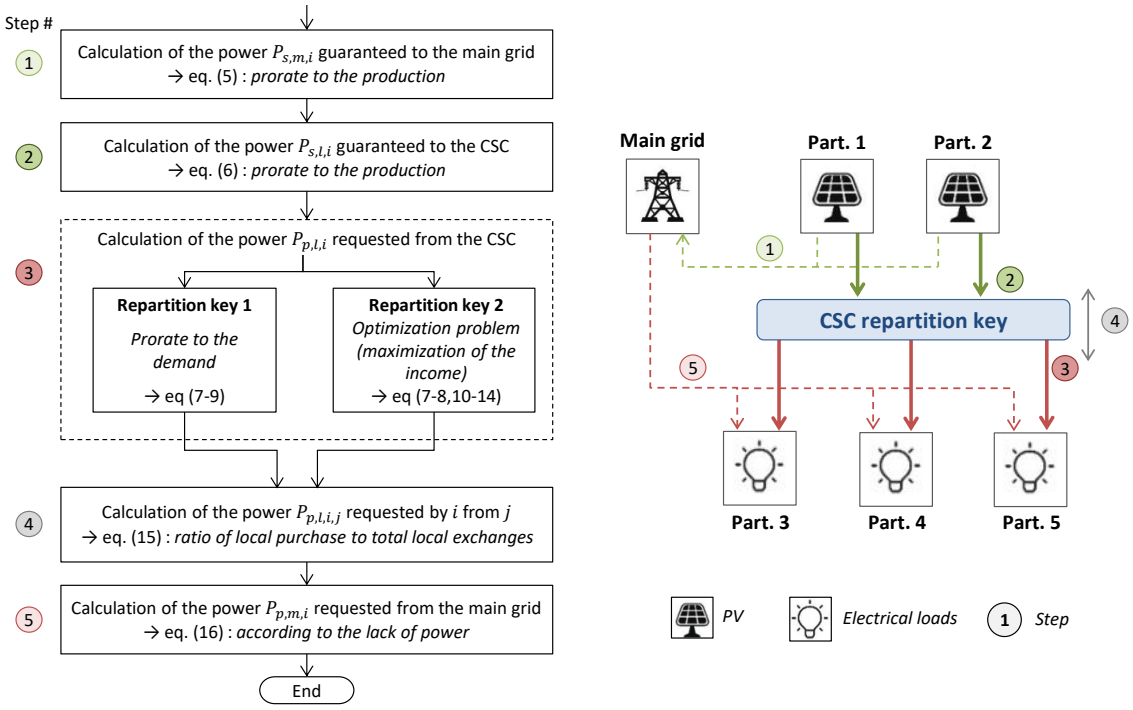

Fig. 4. Calculation steps of the energy allocation algorithm

<u>Step 1</u>: The first step consists of the calculation of the power $P_{s,m,i}$ fed into the main grid, i.e. the part of the generated power which is not used by CSC consumers due to the total power generated ($\sum_{j=1}^{N_p} P_{s,j}$) being larger than the total power needed ($\sum_{j=1}^{N_p} P_{p,j}$). It has been assumed that this excess is shared between producers in proportion to their production $P_{s,i}$ compared to the total production of all the participants, as considered in the regulations in force (ENEDIS, 2019). Each producer sells part of his production to the main grid, which represents the least profitable result for a producer, because the purchase price is low. Thus, the power $P_{s,m,i}$ sold to the main grid by a participant i is defined by:

$$P_{s,m,i} = \max\left(0, \left(\sum_{j=1}^{N_p} P_{s,j} - \sum_{j=1}^{N_p} P_{p,j}\right)\frac{P_{s,i}}{\sum_{j=1}^{N_p} P_{s,j}}\right) = \max\left(0, P_{s,i}\left(1 - \frac{\sum_{j=1}^{N_p} P_{p,j}}{\sum_{j=1}^{N_p} P_{s,j}}\right)\right) \quad (5)$$

It should be noted that if the total power generated $\sum_{j=1}^{N_p} P_{s,j}$ is lower than the total power demanded $\sum_{j=1}^{N_p} P_{p,j}$, the power $P_{s,m,i}$ is zero for all participants.

<u>Step 2</u>: The power $P_{s,l,i}$ guaranteed to the CSC by the producer i is deduced from the previous result according to:

$$P_{s,l,i} = P_{s,i} - P_{s,m,i} \quad (6)$$

From these results, it can be noted that the total power guaranteed by the producers to the community is at most equal to the total power requested by the consumers ($\sum_{j=1}^{N_p} P_{s,l,j} \leq \sum_{j=1}^{N_p} P_{p,j}$). Moreover, the part of the energy generated by each producer that is used in the CSC operation is proportional to their part in production, i.e. to their investments (the producers who have invested the most, therefore those who have produced the most, have the most energy allocated to the community). The power $P_{s,l,i}$ will be allocated between purchasers (i.e. the calculation of the power $P_{s,l,i,j}$ guaranteed by producer i to each consumer j) after the computation of the repartition key presented in the next paragraph.

Step 3: The total power $\sum_{j=1}^{N_p} P_{s,l,j}$ guaranteed to the CSC operation by producers has to be allocated between consumers thanks to a repartition key, so as to determine the power $P_{p,l,i}$ that each consumer i requests from the CSC operation. This result will be used to calculate the individual-to-individual power exchanged ($P_{p,l,i,j} = P_{s,l,j,i}$). Regardless of the repartition key applied, the allocated power $P_{p,l,i}$ cannot exceed the participant' consumption $P_{p,i}$:

$$0 \leq P_{p,l,i} \leq P_{p,i} \tag{7}$$

Moreover, the total power requested by the CSC operation from the producers must be equal to the total power guaranteed by the producers to the CSC operation:

$$\sum_{i=1}^{N_p} P_{p,l,i} = \sum_{j=1}^{N_p} P_{s,l,j} \tag{8}$$

Repartition key 1 (K1): The first key considered is the default key for French regulations (French Government, 2017), which consists of allocating the total power $\sum_{j=1}^{N_p} P_{s,l,j}$ guaranteed to the CSC among the consumers in proportion to their consumption compared to the total consumption of all the participants. This key is based on a pro rata calculation according to the demanded power, with the power $P_{p,l,i}$ defined as:

$$P_{p,l,i} = \frac{P_{p,i}}{\sum_{k=1}^{N_p} P_{p,k}} \times \sum_{j=1}^{N_p} P_{s,l,j} \tag{9}$$

Repartition key 2 (K2): the second repartition key investigated in this article is based on an optimization problem. Current regulations allow a custom key, as long as the rules are established before the start of the CSC operation (French Government, 2017). The purpose of this key is to obtain a distribution that maximizes the income of producers and improves the profitability of the investments, by selling as much energy as possible to

the consumers who have the highest purchase price. Indeed, the first repartition key does not always lead to suitable profit, as in priority the energy is allocated to the participants with the highest consumption, regardless of their purchase price. It should be emphasized that the purchase prices considered in this second repartition key are defined before the start of the CSC operation, according to the contract established between the consumer and the supplier. Thus, the consumer cannot decide to change its value at will during the CSC operation, unlike the situation in a dynamic energy market in which auctions are allowed (Capper et al., 2022; Javadi et al., 2022). This second repartition key is formulated according to the following equations:

$$P_{p,l} = \arg\max(c_{p,l,sp}^{t} \bar{P}_{p,l} \Delta t) \tag{10}$$

$$P_{p,l} = \begin{bmatrix} P_{p,l,1} & \cdots & P_{p,l,i} & \cdots & P_{p,l,N_p} \end{bmatrix} \tag{11}$$

$$c_{p,l,sp} = [c_{p,l,sp,1} \quad \cdots \quad c_{p,l,sp,i} \quad \cdots \quad c_{p,l,sp,N_p}]^t \tag{12}$$

$$\bar{P}_{p,l} = \begin{bmatrix} \bar{P}_{p,l,1} & \cdots & \bar{P}_{p,l,i} & \cdots & \bar{P}_{p,l,N_p} \end{bmatrix}^t \tag{13}$$

where $P_{p,l}$ is the vector containing the optimal solution of allocated power $P_{p,l,i}$ for each participant, $\bar{P}_{p,l}$ the vector of decision variables of the optimization problem (i.e. the allocated powers), $c_{p,l,sp}$ the vector containing the component of the electricity purchase cost that is related to the supply cost (this cost determines the remuneration of the producer, as described in Section 3.2) [€/kWh] and Δt the time step [h]. To be feasible, the solution must satisfy certain constraints. The allocated power $\bar{P}_{p,l,i}$ cannot exceed the power $P_{p,i}$ demanded by the consumer:

$$0 \leq \bar{P}_{p,l,i} \leq P_{p,i} \tag{14}$$

Moreover, the total allocated power $\sum_{i=1}^{N_p} \bar{P}_{p,l,i}$ must be equal to the total power guaranteed by the producers $\sum_{i=1}^{N_p} P_{s,l,i}$ as stated in eq. (8). This optimization problem is a linear programming problem which can be easily solved. In this work, we used the *linprog* function available in the MATLAB scientific environment. This problem could also be solved with a rule-based algorithm, consisting of ordering the values of purchase prices and allocating energy according to this order.

Step 4: Once the powers $P_{p,l,i}$ are calculated by one of the repartition keys, an individual-to-individual allocation is needed for individual billing purposes, by defining the amount of energy that each consumer purchases from each producer. As several producers participate in the operation and as their benefits are related to the consumers' purchase price, the individual allocation has to distribute between the producers the benefits brought

by a sale to the consumers having the highest purchase price. Thus, it is considered in this study that the individual allocation is carried out in proportion to the local purchase of the consumer compared to the sum of all local exchanges. Thus, the exchange between a consumer i and a producer j is computed as:

$$P_{p,l,i,j} = P_{s,l,j,i} = \frac{P_{p,l,i}\, P_{s,l,j}}{\sum_{k=1}^{N_p} P_{s,l,k}} \tag{15}$$

where $P_{p,l,i,j}$ is the power requested by i from j and $P_{s,l,j,i}$ the power guaranteed by j to i. In other words, for example, if the power $P_{p,l,i}$ requested from the CSC operation by a consumer i represents 25% of the total of local exchanges, this consumer purchases from each producer 25% of its local sale. From the opposite point of view (i.e. the individual allocation of the sale), if the power $P_{s,l,j}$ guaranteed by a producer j to the CSC represents 50% of local exchanges, this producer sells to each consumer 50% of its local purchase.

Step 5: Finally, the power drawn from the main grid by the consumer i is deduced from $P_{p,i}$ and $P_{p,l,i}$:

$$P_{p,m,i} = P_{p,i} - P_{p,l,i} \tag{16}$$

To illustrate the methodology and the effect of the two repartition keys, an example of power allocation results on a small number of participants (two producers and two consumers) and for one time sample (Δt = 30 min) is given in Table 1, for the case with $\sum_{j=1}^{N_p} P_{s,j} < \sum_{j=1}^{N_p} P_{p,j}$.

Table 1: Example of power allocation (the case when total power generated is lower than total power needed)

Participant index i	$P_{s,i}$ [kW]	$P_{p,i}$ [kW]	$c_{p,l,sp,i}$ [€/kWh]	$P_{s,m,i}$ [kW]	$P_{s,l,i}$ [kW]	$P_{p,l,i}$ [kW] K1	$P_{p,m,i}$ [kW] K1	$P_{p,l,i}$ [kW] K2	$P_{p,m,i}$ [kW] K2
1	400	0	-	0	400	0	0	0	0
2	100	0	-	0	100	0	0	0	0
3	0	200	0.0905	0	0	166.7	33.3	200	0
4	0	400	0.0880	0	0	333.3	66.7	300	100
Total	500	600	-	0	500	500	100	500	100

The individual allotment described in Eq. (15) leads to the following results for the first repartition key (K1): participant 3 purchases $P_{p,l,3,1}$ = 133.4 kW from producer 1 and $P_{p,l,3,2}$ = 33.3 kW from producer 2. Participant 4 purchases $P_{p,l,4,1}$ = 266.6 kW from producer 1 and $P_{p,l,4,2}$ = 66.7 kW from producer 2. For the second repartition key (K2), the individual-to-individual allocation leads to: $P_{p,l,3,1}$ = 160 kW, $P_{p,l,3,2}$ = 40 kW, $P_{p,l,4,1}$ = 240 kW and $P_{p,l,4,2}$ = 60 kW. With the second repartition key, participant 3 obtains more energy from the producers than participant 4 does, as its purchase price is higher. The income of producer 1 is 17.76 € for K1 and 17.8 € for K2.

For producer 2, the income is 4.43 € for K1 and 4.45 € for K2. Thus, with the repartition key K2, the producers' income is increased.

Another example of power allocation results is given in Table 2 in the case where $\sum_{j=1}^{N_p} P_{s,j} > \sum_{j=1}^{N_p} P_{p,j}$. For this second example, the two repartition keys lead to the same results since the generated power is sufficient to supply all the demand. Thus, consumers purchase all the electricity that they need from the CSC producers, regardless of the repartition key. The individual allotment described in Eq. (15) results in the following distribution: $P_{p,l,3,1}$ = 142.9 kW, $P_{p,l,3,2}$ = 57.1 kW, $P_{p,l,4,1}$ = 285.7 kW and $P_{p,l,4,2}$ = 114.3 kW. The income is 19.04 € for producer 1 and 7.61 € for producer 2.

Table 2: Example of power allocation (the case when total power generated is greater than total power needed)

Participant index i	$P_{s,i}$ **[kW]**	$P_{p,i}$ **[kW]**	$c_{p,l,sp,i}$ **[€/kWh]**	$P_{s,m,i}$ **[kW]**	$P_{s,l,i}$ **[kW]**	$P_{p,l,i}$ **[kW] K1**	$P_{p,m,i}$ **[kW] K1**	$P_{p,l,i}$ **[kW] K2**	$P_{p,m,i}$ **[kW] K2**
1	1000	0	-	571.4	428.6	0	0	0	0
2	400	0	-	228.6	171.4	0	0	0	0
3	0	200	0.0905	0	0	200	0	200	0
4	0	400	0.0880	0	0	400	0	400	0
Total	1400	600	-	800	600	600	0	600	0

3.2. Economic assessment

The rules presented in the previous section concerning energy allocation allows energy exchanges between producers, consumers and the main grid to be individually quantified. Once this step has been completed, the billing of the energy purchases and sales can be assessed following the methodology described below.

Regardless of the consumer and the producer from whom the energy is purchased, an electricity purchase tariff is made up of three costs, a distribution common to many European countries (European Council, 2014). The first component is related to the energy supply cost, which includes the generation cost of electricity, along with that of trading and selling. This cost, denoted by the index sp in the following equations, represents the remuneration of the producer. The second component, denoted by the index gr, is the cost dedicated to the use of the public electric grid for the transport and distribution of electricity. The third corresponds to taxes and is denoted hereafter by the index tax. The value of these three components depends on the energy source (either the main grid or a CSC operation producer). However, it is assumed that the total purchase price is the same for all CSC producers (i.e. there is no concurrence between the CSC operation producers in terms of selling price) and that the cost components do not differ according to the producer. Thus, for a consumer i, the tariff $c_{p,m,i}$ of

301 the electricity purchased from the main grid and the tariff $c_{p,l,i}$ of the electricity purchased from a CSC operation
302 producer (in €/kWh) are defined by:

$$c_{p,m,i} = c_{p,m,sp,i} + c_{p,m,gr,i} + c_{p,m,tax,i} \quad (17)$$

$$c_{p,l,i} = c_{p,l,sp,i} + \beta_{gr}\, c_{p,l,gr,i} + c_{p,l,tax,i} \quad (18)$$

303 where β_{gr} is a coefficient allowing an exemption from the network usage tariff $c_{p,l,gr,i}$ (with $0 \leq \beta_{gr} \leq 1$, 0
304 meaning total exemption and 1 no exemption). This is considered in the sensitivity analysis section of this paper
305 (4.3), showing the benefits brought by a partial or total exemption of this cost for the electricity purchased from
306 the CSC. While the values of the taxes and the grid use cost are set by regulations and can differ between the
307 main grid and the CSC (Carenco et al., 2020), the supply cost of electricity purchased from a CSC producer
308 ($c_{p,l,sp,i}$) can be set as desired. A trade-off has to be found between a low price which will be attractive to the
309 consumer (it will improve savings on the invoice) and a high price which will be interesting for the producer,
310 since this cost will determine producer' remuneration. To study the impact of this trade-off, a coefficient α_p is
311 introduced to quantify the ratio between the main grid electricity cost $c_{p,m,i}$ and the local cost of electricity $c_{p,l,i}$,
312 such as:

$$c_{p,l,i} = \alpha_p\, c_{p,m,i} \quad (19)$$

313 The electricity purchase costs are time-dependent, as there are low and high price periods during a day, as well
314 as seasonal periods. Thus, within the CSC operation, the purchase price differs according to the consumer and
315 the price period. For a period of K time samples and a participant i, the total bill $C_{p,m,i}$ [€] for the electricity
316 purchased from the main grid and the total bill $C_{p,l,i}$ [€] for the electricity purchased from the CSC producers are
317 defined by:

$$C_{p,m,i} = \sum_{k=1}^{K} P_{p,m,i}(t_k)\, c_{p,m,i}(t_k)\, \Delta t \quad (20)$$

$$C_{p,l,i} = \sum_{k=1}^{K} \sum_{j=1}^{N_p} P_{p,l,i,j}(t_k)\, c_{p,l,i}(t_k)\, \Delta t \quad (21)$$

318 For producers, remuneration is defined by the supply cost of the purchaser bill. For a producer i and a period
319 of K time samples, the total remuneration $C_{s,m,i}$ [€] brought by the sale of electricity to the main grid and the
320 total remuneration $C_{s,l,i}$ [€] brought by the sale to the CSC operation consumers are defined by:

$$C_{s,m,i} = \sum_{k=1}^{K} P_{s,m,i}(t_k)\, c_{s,m}(t_k)\, \Delta t \tag{22}$$

$$C_{s,l,i} = \sum_{k=1}^{K} \sum_{j=1}^{N_p} P_{s,l,i,j}(t_k)\, c_{p,l,sp,j}(t_k)\, \Delta t \tag{23}$$

where $c_{s,m}$ is the price of the electricity sold to the main grid [€/kWh], which is the same for all producers.

4. Results

The methodology described in the previous section is validated by a simulation of an industrial case study. The aim of this section is to show the benefits for the participants of integrating a CSC operation and to assess the effectiveness of the proposed repartition keys. Moreover, a sensitivity analysis can reveal the impact of economic parameters related to the choice of the CSC electricity price and the exemption of grid use tariff.

4.1. Case study description

The case study considered in this paper deals with an industrial framework involving several companies in a seaport area in the city of Saint-Nazaire, France. The theoretical CSC operation includes twelve buildings, for which the consumption characteristics are given in Table 3. The power $P_{dem\ max}$ is the maximum load power of each participant and the energy E_{dem} corresponds to the energy consumed annually by the loads. The data related to the load demand of participants is taken from real measurements over a one-year period (2019). Among these participants, it is presumed that six buildings have PV panels (Table 3), with an installed power $P_{pv\ inst}$ sized to maximize their individual self-consumption while taking the area available in the roofs into account. The total installed power reaches 3 MW, corresponding to the maximum installed power allowed by current regulations for a CSC operation in France (French Government, 2017). The energy E_{gen} corresponds to the annual energy generated by PV panels.

Table 3: Data of participants of the CSC operation

Participant index	$P_{dem\ max}$ [kW]	E_{dem} [MWh/y]	$P_{pv\ inst}$ [kW]	E_{gen} [MWh/y]
1	2147	5047	1865	2227
2	126	264	531	634
3	378	284	0	0
4	563	1166	0	0
5	59	74	505	603
6	16	71	5	5
7	1134	615	22	25
8	48	119	0	0
9	767	371	0	0
10	41	139	59	70
11	600	787	0	0
12	2400	10800	0	0
Total	8279	19737	3000	3564

For each participant, the profiles of the purchase price $c_{p,m,i}$ of the electricity drawn from the main grid for a winter and a summer day are given in Fig. 5 and Fig. 6, respectively. For most participants (except 3, 6 and 12), a peak price period exists in the morning (between 8 a.m. and 10 a.m.) and in the afternoon (between 6 p.m. and 8 p.m.). It should be highlighted that participant 12, corresponding to the hydrogen producer, has the lowest purchase price due to its high consumption level and a subsidized tariff due to hydrogen production.

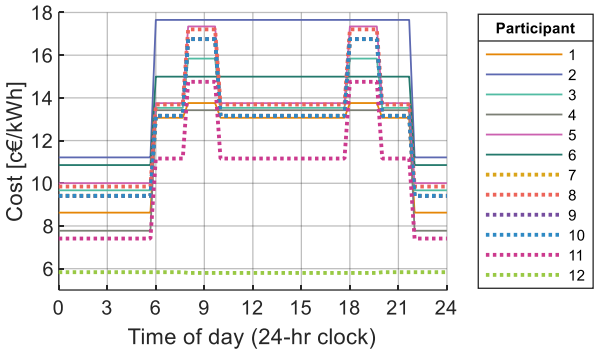

Fig. 5. CSC participants electricity purchase prices $c_{p,m,i}$ for a winter day

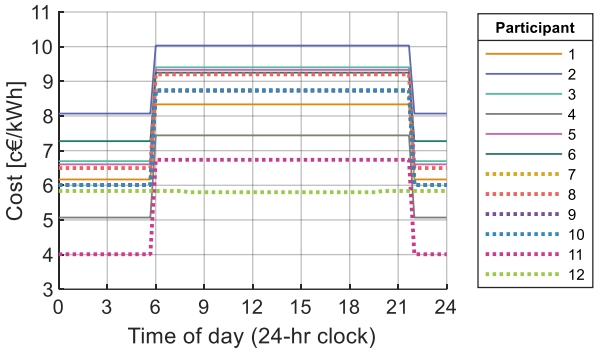

Fig. 6. CSC participants electricity purchase prices $c_{p,m,i}$ for a summer day

As a baseline scenario, it has been assumed in this article that electricity purchased from any CSC producer would be 5% cheaper than electricity purchased from the main grid (α_p = 0.95), irrespective of the time of day and of the season. Moreover, no exemption of grid use tariff has been considered (β_{gr} = 1) in the baseline scenario. Thus, considering these assumptions and equations (17)-(19), the profiles of the supply cost $c_{p,l,sp,i}$ of electricity purchased from CSC producers are given in Fig. 7 (winter day) and Fig. 8 (summer day). These prices correspond to the remuneration of producers who will sell energy to these participants (see Eq. (18) and (23)).

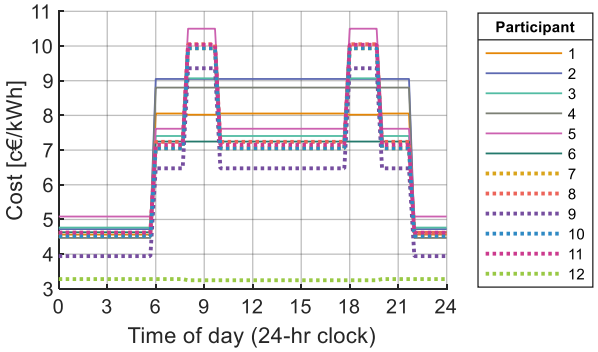

Fig. 7. Supply cost $c_{p,l,sp,i}$ of the local electricity purchase price for a winter day

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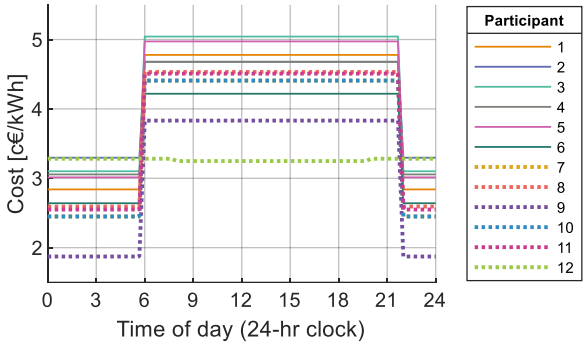

Fig. 8. Supply cost $c_{p,l,sp,i}$ of the local electricity purchase price for a summer day

353

354 For the electricity sold to the main grid by producers, the selling price is set to $c_{s,m}$ = 4 c€/kWh regardless of
355 the producer.

356 *4.2. Comparisons of CSC scheme results*

357 This section aims to study the benefits of setting up a CSC operation, as well as to show the consequences of
358 the choice of a repartition key. Three scenarios are compared according to the CSC scheme:

359 • Scenario A: no CSC, only individual self-consumption;
360 • Scenario B: CSC with the default repartition key based on consumption prorate (K1);
361 • Scenario C: CSC with the optimized repartition key based on the maximization of producer income (K2);

362 The PV sizing is the same in all three scenarios. It should to be noted that this CSC operation is not yet
363 operational and the PV panels are not yet installed. Thus, the economic results are presented in such a way as to
364 identify for the producers whether or not it is interesting to integrate a CSC operation, and if so, with which
365 repartition key. The calculation of the payback period will be considered, to evaluate the profitability of
366 investments made by the participants with a producer role. This corresponds to the ratio between investments
367 and the annual net benefits as explained in (Roy et al., 2021). The annual net benefit is the difference between
368 income (bill savings and sale of electricity to CSC participants and the main grid) and expenses (PV operational

costs). For all participants, the electricity purchase bill savings for each scenario will be calculated by comparing the fictitious purchase bill (thus, with PV production) with the current electricity purchase bill for which all the electricity is purchased from the main grid (thus, no PV production).

The results related to the energy allocation obtained for each scenario are given in Figs. 9 and 10. Fig. 9 shows the origin of the energy purchased by each of the twelve consumers. The distributions obtained show that individual self-consumption can represent a significant proportion of the energy supply, especially for participants 1, 2, 5 and 10. The integration into a CSC operation is beneficial for all participants as it allows them to decrease the rate of energy drawn from the main grid (scenarios B and C). When the optimized repartition key is applied (scenario C), the share of energy purchased from the CSC is significantly increased for some consumers (participants 3, 4, 6, 7, 8, 9 and 11). Indeed, these participants have the highest supply costs, thus they are the most interesting purchasers for producers. For participant 12, the optimized key does not bring a positive effect. Indeed, it decreases the amount of local energy allocated, because of the low supply cost of this participant, which gives it the lowest priority for the allocation of energy.

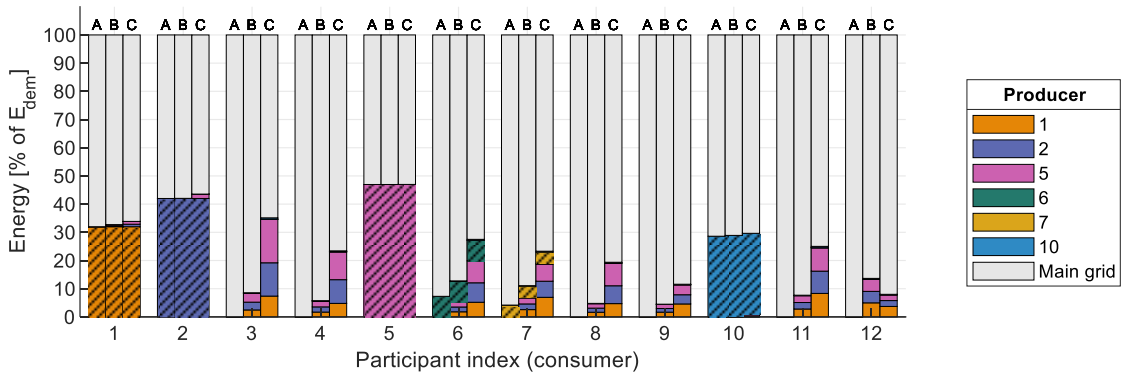

Fig. 9. Source of the electricity purchased by each consumer for scenarios A (without CSC), B (CSC with K1) and C (CSC with K2), expressed as a percentage of the total energy requested by the consumer (the hatched areas represent individual self-production and the top light grey bars purchase from the main grid)

In Fig. 10, the energy allocation is plotted from the opposite point of view. For each producer, the bar graph indicates the purchasers of generated energy. For several producers (1, 6, 7 and 10), individual self-consumption represents the main use of generated energy. It appears that participants 6 and 7 use almost all the energy they generate. Thus, their production is not useful for the CSC operation. The results presented on this graph also show that purchase from the hydrogen producer (participant 12) represents a significant part of the energy sold to the CSC operation by the producers when the default repartition key is applied (scenario B), since this participant has the highest energy demand. This rate is reduced when the optimized key is applied (scenario C). Finally, it can be seen that for producers 2 and 5, the integration into a CSC operation has a positive effect in terms of energy use because most of the power they generate is allocated to CSC participants. Regardless of the

repartition key, the integration into a CSC operation allows all producers to avoid sale to the main grid, thereby avoiding sale at a low price.

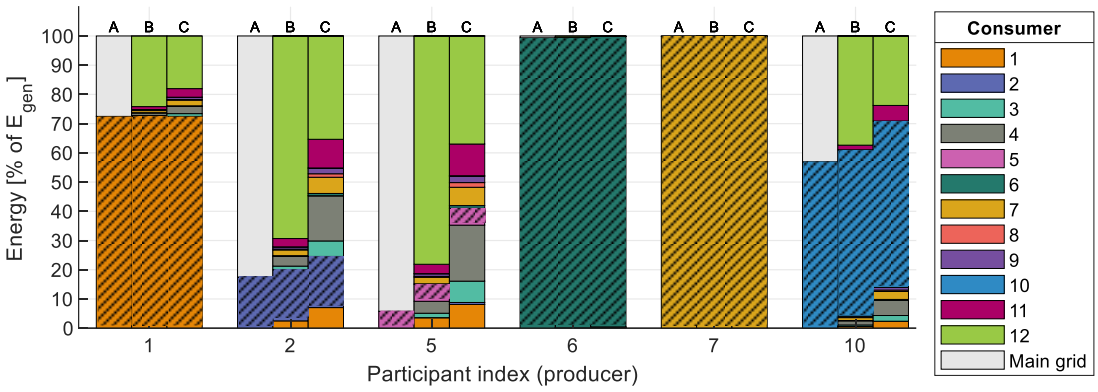

Fig. 10. Use of the energy sold by each producer for each scenarios A (without CSC), B (CSC with K1) and C (CSC with K2), expressed as percentage of the total energy generated by a producer (the hatched areas represent individual self-consumption and the top light grey bars sale to the main grid)

The energy allotments shown in the graphs previously discussed have consequences on economic results. Savings on the electricity purchase bill for each participant and each scenario are shown in Fig. 11. For several participants with a producer role (1, 2, 5 and 10), the savings are high, between 25% and 40%, mainly due to the large amount of individually self-consumed energy (Fig. 9). These results show that for most of the participants, the optimized repartition key (scenario C) allows purchase bill savings to be increased compared to the case without CSC (scenario A) or with CSC governed by the default key (scenario B), as some consumers receive more energy from the CSC operation. As can be seen in Fig. 9, the optimized key leads to lower savings for participant 12 as less local energy is allocated to this consumer (scenario C).

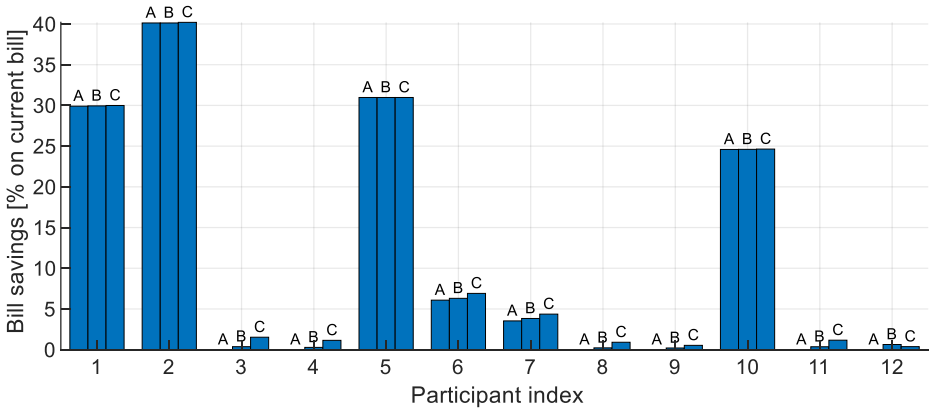

Fig. 11. Electricity purchase bill savings for each participant and each scenario, compared to a case without PV production

The payback period expected for participants who play a producer role is given in Fig. 12 for each scenario. The values obtained show that integration into a CSC operation is only interesting for the producers if an optimized repartition key is applied (scenario C). Indeed, if the default key is considered (scenario B), producers

will potentially have to sell energy to low purchase-price consumers, sometimes ones on a lower tariff than the main grid (for example to the participant 12). This lengthens the payback period, mainly for participants 2 and 5. The proposed repartition key based on maximization of producer income allows profitability for the producers to be improved. Thus, the payback periods obtained for scenario C are shorter than those obtained only with individual self-consumption (scenario A), which could foster the integration into such a CSC operation of participants who have PV panels.

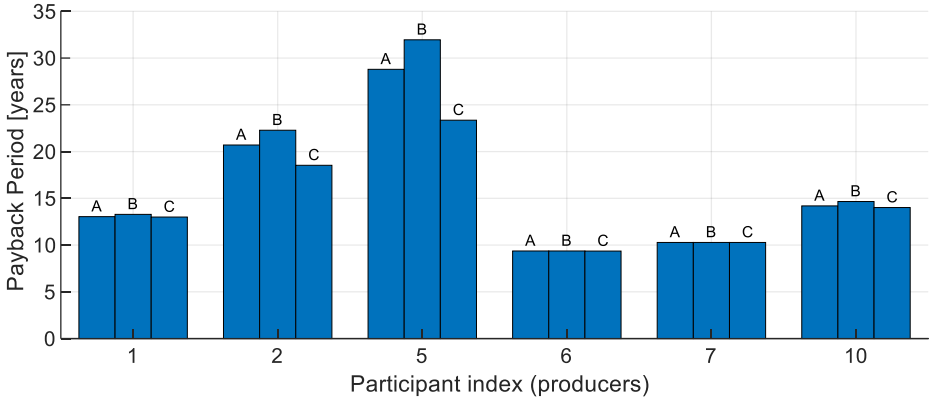

Fig. 12. Payback period for the participants with a producer role, for each scenario

Finally, in Table 4 the performances of the three scenarios are compared from the point of view of the whole CSC operation. The results for the considered case study show that a CSC operation allows the generated energy to be fully used in the industrial area, as no surplus is sold to the main grid, mainly due to the presence of a hydrogen producer which represents a high load demand. Moreover, the self-sufficiency rate of the community is doubled with a CSC operation. From the economic point of view, it can be seen that purchase bill savings are improved with a CSC operation. However, an optimized repartition key is needed and preferable for the profitability of producers (scenario C), since with the non-optimized key, energy is allocated regardless of the purchase cost, resulting in a decrease of income, thus a worse payback period (scenario B).

Table 4: Results at the scale of the CSC operation

Criterion	Scenario A	Scenario B	Scenario C
Self-consumption [% of generated energy used by CSC consumers]	51.35	100	100
Self-sufficiency [% of energy needed supplied by CSC producers]	9.27	18.06	18.06
Purchase bill savings [% of current bill]	-11.3	-11.64	-11.72
Payback period [years]	19.94	20.33	19.49

The results obtained in this study confirm the trends observed in several publications (Albouys-Perrois et al., 2022; de Villena et al., 2022; Mustika et al., 2022b), namely an improvement of the self-consumption and the self-sufficiency rates and an increase of the bill savings by joining a CSC operation, considering a repartition key based on energy criteria (scenario B). However, the optimized repartition key proposed in this paper allows these results to be improved by allocating the energy in a way that maximizes the income (scenario C). Also, this study considers the profitability as an evaluation criterion, unlike past studies. The optimized repartition key proposed here makes it possible to reduce the payback period, therefore the profitability is improved for the producers, unlike scenario B (energy prorate rules) in which the profitability is not an objective.

4.3. Sensitivity analysis concerning economic assumptions

The results analysed in the previous section were based on economic assumptions, considering the most likely case according to current regulations, i.e. with a local price just below the current purchase price (α_p = 0.95) and no exemption of the grid use tariff (β_{gr} = 1). However, these parameters could have a significant influence on benefits for participants and the profitability of investments made by the producers. It has to be noted that the current regulations are under discussion to state whether the grid use tariff could be decreased in the case of a CSC operation, as this does not use the same portion of the grid as a situation without CSC. To quantify this influence, a sensitivity analysis performed on these parameters is described in this section, assuming that the K2 optimized repartition key is applied.

The purchase bill savings the participants obtain by integrating into the CSC operation depends on the price reduction coefficient α_p described in (19). Thus, the sensitivity of the electricity bill savings of each participant to the local tariff coefficient α_p is proposed in Fig. 13, considering a CSC purchase price from -25% to +25% compared to the current purchase price ($0.75 \leq \alpha_p \leq 1.25$). It should be noted that $\alpha_p > 1$ means that the electricity purchased from CSC operation producers is more expensive than that purchased from the main grid, which is favourable for the producers to improve profitability. The curves obtained show that a variation from α_p = 0.95 to α_p = 0.75 helps purchase bill savings to be increased, but the gain is low. However, the impact is more pronounced and disadvantageous when energy price is increased ($\alpha_p > 1$), meaning that it is less interesting for the participants to integrate into a CSC operation, especially those who are only consumers. Indeed, the bill of such participants is increased (negative savings values). From the global point of view (i.e. the

whole CSC operation), the bill savings are between 13.3% (for α_p = 0.75) and 9.2% (for α_p = 1.25), thus the CSC operation remains beneficial even if the savings decrease when the price coefficient is increased.

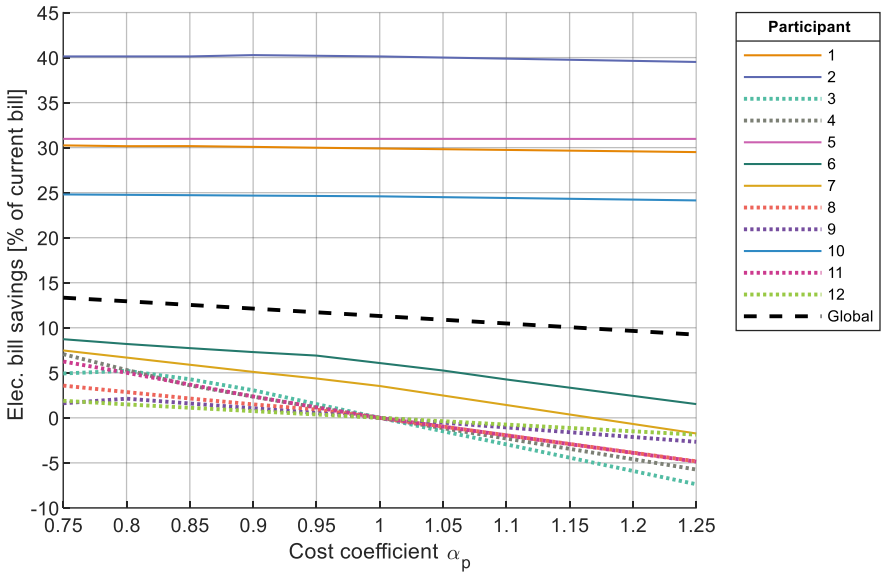

Fig. 13. Sensitivity of the electricity purchase bill savings to the parameter α_p related to the CSC electricity purchase price (dotted lines represents the participants with a consumer role, continuous lines the participants with a dual producer and consumer role, dashed line the saving for the whole CSC operation)

The profitability of the investments made by the producers depends on both economic parameters α_p and β_{gr}. Indeed, in the case of a grid tariff exemption (β_{gr} < 1), the supply cost $c_{p,l,sp,i}$ of the electricity purchased by a consumer i from a CSC operation producer can be increased to reach the total price set according to the coefficient α_p. Thus, the sensitivity to the economic parameters α_p and β_{gr} of the payback period expected for each producer is presented in Fig. 14. Three cases are considered for the grid use tariff: no exemption (β_{gr} = 1, as in the baseline scenario), half-exemption (β_{gr} = 0.5) and full exemption (β_{gr} = 0). The results obtained show that the choice of economic parameter values mainly impacts four participants (1, 2, 5 and 10). An exemption of the grid use tariff could help decrease the payback period by several years, while maintaining an interesting tariff for the consumers (α_p < 1). Otherwise, without exemption, the only solution for an improvement of the profitability of producers' investments is an increase of the purchase price for the consumers, to a value higher than the price set for purchase from the main grid (α_p > 1). However, this solution is not advisable for the consumers. Thus, the results presented in Fig. 13 and Fig. 14 show that a trade-off must be found between the savings of the participants and the payback period of the producers, depending on the choice of the price coefficient α_p and considering a possible exemption of the grid use tariff β_{gr}.

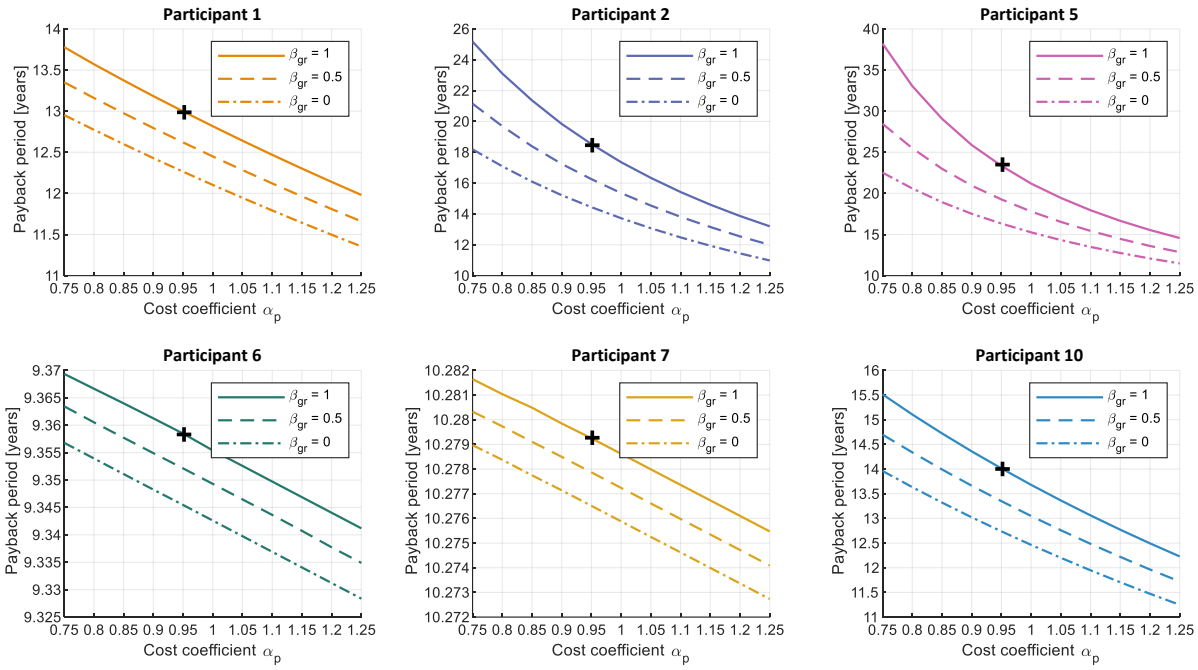

Fig. 14. Sensitivity of the payback period to economic parameters α_p and β_{gr} for the participants with a producer role (marker indicates the results of the baseline scenario discussed in section 4.2)

5. Conclusion

In this paper, a comparison of possible schemes for a CSC operation in a multi-energy microgrid has been presented. An optimized repartition key has been designed to maximize the income for producers, while the default repartition key proposed by current regulations in force in France is based on an allocation prorate to the demand of the consumers. The analysis of the results obtained upon simulation shows that the energy allotment of the energy generated in the CSC operation is more favourable for more participants when the optimized key is computed, in terms of profitability for producers and purchase bill savings for consumers. Indeed, the default key can lead to less profitable results for producers as main consumers do not always show the highest purchase prices. Moreover, the participation of producers in a CSC operation is favourable in terms of energy use and sale, as the surplus of generated energy not consumed individually can be shared with neighbours instead of being sold to the main grid at a low price. The results show that the reduction in the payback period provided by the optimized repartition key is between several months and 5 years, compared to a case without CSC. Also, the community bill savings reach 11.7% when CSC with optimized key is considered. In a context of a multi-energy microgrid with needs of hydrogen production, a CSC operation seems to be an interesting marketing policy, as energy needs can be high, especially during the day, i.e. when an excess of generated power exists. The energy indicators of the community show that the self-sufficiency rate reaches 18.06% with CSC (compared to 9.27%

without CSC) and the self-consumption rate reaches 100% (compared to 51.35% without CSC). The sensitivity analysis performed in this paper has shown that an exemption of the public grid use tariff (which is related to the national distribution grid) could be beneficial for producers and could allow the purchase price of the consumers to be decreased.

The study carried out in this work dealt with a French case study with the regulation in force in this country, but the methodology proposed for the post allotment of excess energy generated could be applied to other case studies in other countries, taking the local regulations into account. The methodology is also scalable since other repartition keys can be proposed. Moreover, the positive trends observed concerning the optimized repartition key and results related to the industrial and multi-energy context seem to be significant for similar trends in other case studies. More profitable results can be expected given the upward trend in energy prices, as the CSC operation allows consumers to avoid purchasing part of their energy needs from the main grid at a high price. It can be noted that the PV sizing considered in this paper, therefore the PV penetration level, depends on the characteristics of the participants and is constrained by the maximum total power set by the regulation (3 MW). Several limitations can be identified for the implementation of the proposed approach in practical applications. The establishment of a contract including all possible issues can be difficult. For example, the unavailability of the measurements due to a dysfunction of the meters must be considered in the contract. Moreover, the governance of a CSC operation requires a moral organizer to manage the community, which can be difficult to find, as the companies and industries have sometimes no experience for such an energy community manager role. Also, the participants must agree on the repartition key, but each of them may have different expectations.

Several perspectives of the work presented in this paper can be proposed. Firstly, it could be interesting to study whether a better solution could exist considering the repartition of producers and consumers among several CSC operations, to gather participants into smaller operations. Also, other repartition keys could be proposed, for example prorate to the investments or by minimizing the gap between participants' bills savings. Moreover, the impact of the repartition key and the economic assumptions, such as the grid use exemption and local electricity purchase price, on the sizing optimization could be studied. The impact of the constraint related to the maximum installed power could also be investigated. Finally, the integration of demand-side management into the energy management strategies of each participant could be studied, to evaluate how the flexibility of consumer demand could influence the results and, if necessary, how the repartition key should be modified.

CRediT authorship contribution statement

Anthony Roy: Conceptualization, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing - original draft. **Jean-Christophe Olivier, François Auger, Bruno Auvity, Emmanuel Schaeffer, Salvy Bourguet:** Conceptualization, Methodology, Supervision, Project administration, Funding acquisition.

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Nomenclature

Variable	Definition	Unit
i	Participant index	-
k	Time index	-
$\mathcal{I}$	Set of participants of the CSC operation	-
$c_{p,l,i}$	Cost of the electricity purchased from a producer of the CSC operation by a participant i	€/kWh
$c_{p,l,sp,i}$	Supply cost of the electricity purchased from a producer of the CSC operation by a participant i	€/kWh
$c_{p,l,gr,i}$	Grid use cost of the electricity purchased from a producer of the CSC operation by a participant i	€/kWh
$c_{p,l,tax,i}$	Taxes cost of the electricity purchased from a producer of the CSC operation by a participant i	€/kWh
$c_{p,m,i}$	Cost of the electricity purchased from the main grid by a participant i	€/kWh
$c_{p,m,sp,i}$	Supply cost of the electricity purchased from the main grid by a participant i	€/kWh
$c_{p,m,gr,i}$	Grid use cost of the electricity purchased from the main grid by a participant i	€/kWh
$c_{p,m,tax,i}$	Taxes cost of the electricity purchased from the main grid by a participant i	€/kWh
$C_{p,l,i}$	Expenses related to the purchase of electricity from the producers of the CSC operation over a given period	€
$C_{p,m,i}$	Expenses related to the purchase of electricity from the main grid over a given period	€
$C_{s,l,i}$	Income related to the sale of electricity to the consumers of the CSC operation over a given period	€
$C_{s,m,i}$	Income related to the sale of electricity to the main grid over a given period	€
K	Number of time samples of the simulated period	-
N_p	Number of participants	-
$P_{p,i}$	Total power requested (i.e. purchased) by a participant i	kW
$P_{p,l,i}$	Power requested from the CSC operation by a participant i	kW
$P_{p,m,i}$	Power requested from the main grid by a participant i	kW
$P_{s,i}$	Total power fed into (i.e. sold to) the grid by a participant i	kW
$P_{s,l,i}$	Power guaranteed to the CSC operation by a participant i	kW
$P_{s,m,i}$	Power guaranteed to the main grid by a participant i	kW
$\bar{P}_{p,l}$	Vector of decision variables of the energy sharing optimization problem	-
β_{gr}	Exemption rate of grid use cost for electricity purchased from a producer of the CSC operation	-
α_p	Ratio between the cost of electricity purchased from a producer of the CSC operation and the cost of electricity purchased from the main grid	-
Δt	Time step	h

Figures/Tables captions

Figure/Table	Caption	Size	Color
Fig. 1	Layout of the industrial microgrid of the considered CSC operation	Double column	Yes
Fig. 2	Scheme of energy and economic data flows between the entities of the CSC operation considered, according to French regulations	Single column	Yes
Fig. 3	Distribution of the power flows related to participant 1 for a case in which participant 1 sells energy (top scheme) and a case in which participant 1 purchases energy (bottom scheme)	Single column	Yes
Fig. 4	Calculation steps of the energy allocation algorithm	Double column	Yes
Fig. 5	CSC participants electricity purchase prices $c_{p,m,i}$ for a winter day	Single column	Yes
Fig. 6	CSC participants electricity purchase prices $c_{p,m,i}$ for a summer day	Single column	Yes
Fig. 7	Supply cost $c_{p,l,sp,i}$ of the local electricity purchase price for a winter day	Single column	Yes
Fig. 8	Supply cost $c_{p,l,sp,i}$ of the local electricity purchase price for a summer day	Single column	Yes
Fig. 9	Source of the electricity purchased by each consumer for scenarios A, B and C, expressed as a percentage of the total energy requested by the consumer	Double column	Yes
Fig. 10	Use of the energy sold by each producer for each scenarios A, B and C, expressed as percentage of the total energy generated by a producer	Double column	Yes
Fig. 11	Electricity purchase bill savings for each participant and each scenario, compared to a case without PV production	Double column	Yes
Fig. 12	Payback period for the participants with a producer role, for each scenario	Double column	Yes
Fig. 13	Sensitivity of the electricity purchase bill savings to the parameter α_p related to the CSC electricity purchase price	1.5 column	Yes
Fig. 14	Sensitivity of the payback period to economic parameters α_p and β_{gr} for the participants with a producer role	Single column	Yes
Table 1	Example of power allocation (the case when total power generated is lower than total power needed)	Double column	No
Table 2	Example of power allocation (the case when total power generated is greater than total power needed)	Double column	No
Table 3	Data of participants of the CSC operation	Single column	No
Table 4	Results at the scale of the CSC operation	Single column	No