Energy allocation and settlement in collective self-consumption

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***Abstract*—Energy allocation rules are one of the core aspects of collective self-consumption (CSC) regulations. It allows final consumers to share their surplus generation with other CSC members, while keeping their full rights as consumers, i.e., maintaining a supply contract with the retailers of their choice. Some European Union member states regulations use allocation coefficients so that local allocations are integrated with wholesale settlement and directly affect the retailers' billing. Several AC methods have been proposed so far, each one adapted to distribution system operators' settlement procedures with specific rules that can impact the benefits that each CSC member obtain. This paper analyses, assesses and compares two relevant AC methods, namely pre-delivery fixed AC and post-delivery dynamic AC, by developing a settlement formulation for a community with members with flexible assets and different opportunity costs. AC policy recommendations based on findings are provided.**

***Index Terms*— energy communities, collective self-consumption, local energy markets, allocation rules, settlement**

I. Introduction

Empowering final consumers is one of the main drivers towards a cleaner and less reliant on fossil fuels power sector. Generalized small scale distributed renewable generation and storage systems can adapt their energy profiles to match the local available supply and demand also considering the grid needs. This way it can contribute to a better local balancing and to provide services needed to operate the system in a secure way under a high penetration of renewable generation. To achieve these goals, several European Union (EU) member states (MS) are transposing the EU self-consumption directive that allow collective self-consumption (CSC) and sharing local energy [1].

Regulatory proposals are still on development, but relevant cases include France [2], Portugal [3], Spain [4], or Austria, which uses the allocation coefficient (AC) to allow final consumers to share their surplus generation with other local CSC members. In addition, CSC members keep their full rights as consumers, so they can keep or contract the supplier (SUP) of their choice that bills them for the energy they didn´t self-consume. Surplus generation can be sold back to the grid, either directly on the wholesale market or through aggregators. Some regulations allow members to individually contract an aggregator (AGG), while others force the CSC to contract only one AGG to buy the CSC aggregated surplus. In addition, regulation typically states that self-consumption must pay grid tariffs when using the public grid, discounting the grid voltage levels not used. Allocation plays a major role in defining who may benefit from CSC generation, and how much each agent is billed from the grid supply. MS may regulate similar general rules for ACs, but there are relevant differences [5], so assessing the impact of already regulated and innovative ways of using AC helps to understand and achieve the full potential of distributed generation for CSC structures, and to create the conditions to develop local electricity markets (LEMs) [6].

TABLE I. in the appendix, reviews the recent but increasing research on CSC models with the purpose of assessing the novelty of the work proposed in this paper. Fixed, proportional, and dynamic ACs are predominantly simulated, since these are usually the ACs types implemented by most MS regulators. Most papers simulate rather simple CSC composed of prosumers with fixed load and PV panels, assessing their economic viability considering the sharing mechanism. Flexible assets add complexity to the optimization program, especially if proportional AC is used together with battery energy storage systems (BESS), since the dispatch decisions that leads to net consumption affect the energy allocated to all members, adding non-linearity to the problem. To solve this, a predefined BESS rule program is used in [7], [8]. Internal compensations for the energy locally shared are generally considered, but only a few approaches consider explicit post-delivery LEM [9], either with trading resulting directly from fixed [10] and proportional AC [11] allocations, or with dynamic AC reflecting the result of local trading [12], [13]. Few papers assess regulatory aspects, either to compare policy price incentives to CSC [14], or to simulate the impact of regulated AC types [8], [15].

To our knowledge, no work has been done to assess the use of innovative AC types in CSC, including the use of post-delivery LEM with flexible assets. In this work we show that the combination of flexible assets and ACs allocation may trigger undesired behaviours, such as using BESS physical dispatch to arbitrage energy transactions among members with different grid trading prices. In a way, LEM and price arbitrage are inevitable in CSC where members are subject to different price signals from the energy bought from their contracted SUP and sold to their AGG, and regulation should consider this when defining AC rules.

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This work builds upon the CSC settlement structure of [16], and in the CSC with LEM modelling in [9], [17], where allocation rules are limited to strict dynamic AC. Since our focus is to assess the allocation itself, we only describe the main equations of the referred models and the AC constraints needed. We formulate and simulate the dispatch program of an CSC with members with differing price signals and subject to the following AC types: fixed ACs with and without self-allocation, and strict and flexible dynamic ACs. Programming proportional ACs is a complex task due to non-linearity issues and more intricate conditions than fixed and dynamic ACs and will be addressed in future research. The key developments addressed in this paper include:

- Impact of AC types with post-delivery LEM in individual and overall CSC benefits.
- BESS management under several ACs with post-delivery LEM.
- Assessment of CSC arbitrage behaviours and proposal of flexible dynamic ACs to foster competition.
- Assessment of the regulation of different ACs types.

Section II describes the optimization problem, section III presents a case study for a CSC with PV generation and battery energy storage systems (BESS) and analyses the results, and section IV summarizes the main conclusion of this work.

II. AC Types and modelling

In this work, allocations are computed bilaterally to give the model flexibility to simulate CSC under different energy sharing rules, including, not only, AC variants, but also relevant aspects such as the impact of grid tariffs. Although allocations are bilateral, the post-delivery LEM is pool based and provides a unique internal transactions price.

In the EU, the distribution system operator (DSO) is usually responsible for accessing metered data and computing, according to the AC type defined by the CSC and previously communicated to the DSO, the amount of energy allocated and supplied to each CSC member and their surplus. If dynamic ACs are selected, the CSC computes itself their values according to its own criteria, for example to represent the allocations resulting from a LEM trade and sends them to the DSO for validation and computation of the above quantities. The DSO informs of the final allocation results to the CSC and other relevant stakeholders [5].

Figure 1 shows the CSC model used to simulate the allocations for fixed and dynamic AC. For fixed ACs, in step 1 the BESS of CSC member 1 (M1) is optimally dispatched to minimize the CSC costs. In step 2, the energy injected by the CSC members net producers is allocated among the CSC members consuming applying the predefined bilateral fixed ACs. This way, in step 3 the post-delivery LEM trades are computed to be equal to the allocated energies, and step 4 is the computation of the final surplus and supply of each member considering the metered deliveries and energy allocations. For dynamic ACs, the order is reversed, since it is the post-delivery LEM in step 2 that define energy allocations of step 3.

AC types are simulated by running a 2-stage optimization. In stage 1, each member optimizes its own operation, as if they were individual self-consumers, which is used as a reference for comparison in stage 2 to guarantee that no member become worse of. Stage 2 minimizes the CSC's costs. While the first stage is the same in all cases, the second stage is adapted to each AC type.

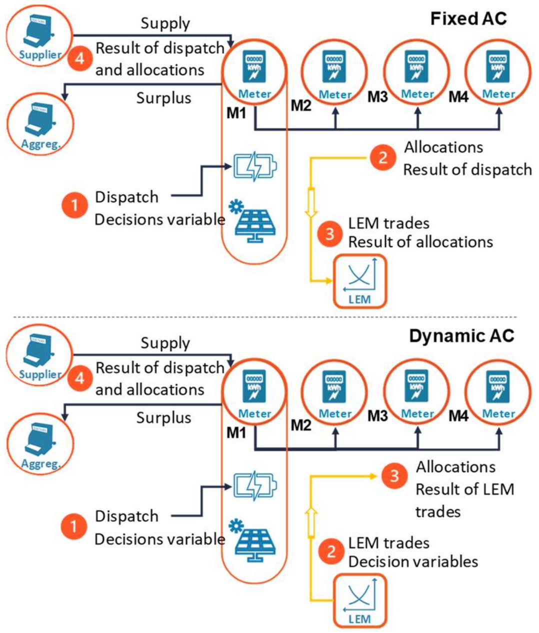

Figure 1. CSC simulation with a) fixed and b) dynamic AC

A. *Stage 1: Individual optimization*

In stage 1 the objective function (1) minimizes the individual costs.

$$min \sum_{t\in T}\left(E^{SUP}_{n,t}\cdot\hat{\lambda}^{buy}_{n,t} - E^{SUR}_{n,t}\cdot\hat{\lambda}^{sell}_{n,t} + \sum_{s\in S} E^{B,D}_{n,s,t}\cdot\hat{\lambda}^{deg}_{n,s}\right), n\in N \quad (1)$$

where, for each CSC member $n \in N$, $E^{SUP}_{n,t}$ is the energy supplied by its retailer at price $\hat{\lambda}^{buy}_{n,t}$, $E^{SUR}_{n,t}$ is the surplus sold to its retailer at feed-in price $\hat{\lambda}^{sell}_{n,t}$, and for each BESS $s \in S$, a degradation cost $\hat{\lambda}^{deg}_{n,s}$ is applied to each discharge $E^{B,D}_{n,s,t}$ to minimize unprofitable BESS cycles. Equation (2) is the energy balance with the grid:

$$E^{CMET}_{n,t} = E^{SUP}_{n,t} - E^{SUR}_{n,t},\ \forall\, t\in T, n\in N \quad (2)$$

where $E^{CMET}_{n,t}$ is the metered net consumption of *n*, where negative values mean injections into the grid. Equation (3) is the energy equilibrium constraint:

$$E^{CMET}_{n,t} = \hat{E}^{C}_{n,t} - \hat{E}^{G}_{n,t} + \sum_{s\in S}\left(E^{B,C}_{n,s,t} - E^{B,D}_{n,s,t}\right),\ \forall\, t\in T \quad (3)$$

where the load $\hat{E}^{C}_{n,t}$ and the generation $\hat{E}^{G}_{n,t}$ profiles are input parameters, and $E^{B,C}_{n,s,t}$ is the energy charged by the BESS. Equation (4) limits the grid exchanges to the contracted power:

$$-\hat{P}^{CPE,max}_{n} \le \frac{E^{CMET}_{n,t}}{\Delta t} \le \hat{P}^{CPE,max}_{n},\ \forall\, t\in T \quad (4)$$

where $\hat{P}^{CPE,max}_{n}$ is the contracted power of *n*. The energy of each BESS is tracked with (5):

$$E^{B}_{n,s,t} = E^{B}_{n,s,t-1} + \left(E^{B,C}_{n,s,t}\cdot\hat{\eta}^{B,C}_{n,s} - \frac{E^{B,D}_{n,s,t}}{\hat{\eta}^{B,D}_{n,s}}\right),\ \forall\, t\in T, s\in S \quad (5)$$

where $E^{B}_{n,s,t}$ is the energy stored by the BESS, and $\hat{\eta}^{B,C}_{n,s}$ and $\hat{\eta}^{B,D}_{n,s}$ are its charging and discharging efficiencies. The state of charge (SOC) is given by (6) and limited by (7), while (8) ensures the SOC is at 50% at the end of the last period.

$$SOC^{B}_{n,s,t} = \frac{E^{B}_{n,s,t}}{\hat{E}^{B,N}_{n,s}}\cdot 100,\ \forall\, t\in T, s\in S \quad (6)$$

$$\widehat{SOC}^{B,min}_{n,s} \le SOC^{B}_{n,s,t} \le \widehat{SOC}^{B,max}_{n,s},\ \forall\, t\in T, s\in S \quad (7)$$

$$SOC^{B}_{n,s,t} \ge 50,\ t = T_{last} \quad (8)$$

where $SOC^{B}_{n,s,t}$ is the SOC of the BESS, $\hat{E}^{B,N}_{n,s}$ is its nominal capacity, $\widehat{SOC}^{B,min}_{n,s}$ and $\widehat{SOC}^{B,max}_{n,s}$ the minimum and maximum SOC, and T_{last} is the last period of the optimization horizon (set to one day). SOC in $t = 0$ is set to 50%. Charging and discharging rates are limited by (9) and (10), which also ensure that the BESS cannot charge and discharge simultaneously.

$$\frac{E^{B,C}_{n,s,t}}{\Delta t} \leq \hat{P}^{B,max}_{n,s} \cdot (\delta^{B,C}_{n,s,t}),\ \forall 1\ t \in T, s \in S \quad (9)$$

$$\frac{E^{B,D}_{n,s,t}}{\Delta t} \leq \hat{P}^{B,max}_{n,s} \cdot (1 - \delta^{B,C}_{n,s,t}),\ \forall\ t \in T, s \in S \quad (10)$$

where $\hat{P}^{B,max}_{n,s}$ is the maximum input and output power of the BESS and $\delta^{B,C}_{n,s,t}$ is binary and equal to 1 when charging. Finally, (11) calculates the individual costs $C^{ind\_1}_{n}$:

$$C^{ind\_1}_{n} = \sum_{t\in T}\left(E^{SUP}_{n,t} \cdot \hat{\lambda}^{buy}_{n.t} - E^{SUR}_{n,t} \cdot \hat{\lambda}^{sell}_{n,t} + \sum_{s\in S} E^{B,D}_{n,s,t} \cdot \hat{\lambda}^{deg}_{n,s}\right) \quad (11)$$

B. Stage 2: CSC optimization

To simulate several AC types, the objective function (12) minimizes the aggregated CSC's costs.

$$min \sum_{t\in T}\left(\sum_{n\in N}\left(E^{SUP}_{n,t} \cdot \hat{\lambda}^{buy}_{n,t} - E^{SUR}_{n,t} \cdot \hat{\lambda}^{sell}_{n,t} + E^{SLC}_{n,t} \cdot \hat{\lambda}^{grid}_{t} + \sum_{s\in S} E^{B,D}_{n,s,t} \cdot \hat{\lambda}^{deg}_{n,s}\right)\right) \quad (12)$$

where $E^{SLC}_{n,t}$ is the self-consumed energy which pays a grid access tariff $\hat{\lambda}^{grid}_{t}$. Equation (2) is replaced by (13) to include LEM trades.

$$E^{CMET}_{n,t} = E^{SUP}_{n,t} - E^{SUR}_{n,t} + E^{PUR}_{n,t} - E^{SALE}_{n,t},\ \forall\ t \in T, n \in N \quad (13)$$

where $E^{PUR}_{n,t}$ and $E^{SALE}_{n,t}$ are the local purchases and sales respectively. The constraints (3)–(10) of stage 1 also apply to stage 2. In CSC, the self-consumption of a member is usually computed as in (14).

$$E^{SLC}_{n,t} = min\left(E^{CMET}_{n,t}, E^{ALC}_{n,t}\right), \forall\ t \in T \quad (14)$$

where $E^{ALC}_{n,t}$ is the total energy allocated to one member from all CSC injecting members $m \in N$, as in (15).

$$E^{ALC}_{n,t} = \sum_{m\in N} E^{ALC}_{n,m,t}, \forall n \in N \quad (15)$$

where $E^{ALC}_{n,m,t}$ is the energy allocated from *m* to *n*, computed by applying the corresponding AC ($\propto_{n,m,t}$) to the energy injected into the grid by m, as in (16).

$$E^{ALC}_{n,m,t} = \propto_{n,m,t} \times\ max\left(0, -E^{CMET}_{m,t}\right),\ \forall\ t \in T \quad (16)$$

In this model, using fixed or dynamic ACs implies computing $E^{ALC}_{n,m,t}$ in different ways, which also has an impact on the LEM transactions, as explained in sections C to F.

C. Fixed AC with self-allocation

The fixed AC $\hat{\propto}_{n,m,t}$ are defined by the CSC prior to the energy delivery, typically at the CSC licensing time, and changes only when members join or quit the CSC. Is this work it is assumed that the CSC defined a simple AC pool-like rule $\hat{\propto}^{init}_{n,t}$, where the proportion allocated to each member is equal, regardless of who is injecting, as in (17).

$$\hat{\propto}_{n,m,t} = \hat{\propto}^{init}_{n,t},\ \forall\ n, m \in N, t \in T \quad (17)$$

The bilateral allocations $E^{ALC}_{n,m,t}$ are computed applying $\hat{\propto}_{n,m,t}$ to (16). This implies that all members have energy allocated to them if there are members injecting, regardless of whether they inject into the grid or not. Although some regulations avoid allocating energy to members injecting into the grid [3], as in Portugal, this work wants to assess if this could be reasonable or not, especially with BESS. Regulators can also set limits to the AC values to force the CSC to only allocate energy physically injected into the grid, which can be modelled with (18).

$$0 \leq \propto_{n,m,t} \leq 1\ \&\ \sum_{m} \propto_{n,m,t}\ \leq 1, \forall\ t \in T \quad (18)$$

Finally, as shown in Figure 1, in this case bilateral LEM transactions $E^{SALE}_{m,n,t}$ and $E^{PUR}_{n,m,t}$ correspond to the bilateral allocations:

$$E^{SALE}_{m,n,t} = E^{ALC}_{n,m,t} = \hat{\propto}_{n,m,t} \times\ max\left(0, -E^{CMET}_{m,t}\right),\ \forall\ t \in T$$
$$E^{PUR}_{n,m,t} = E^{ALC}_{n,m,t},\ \forall\ t \in T \quad (19)$$

Note that, although the energy values of the LEM trades derive from the allocations, the pool-like price was set to the dual variable of (23) as in [9]. Each member's final cost is computed including LEM trades in (20) for all AC types.

$$C^{ind\_2}_{n} = \sum_{t\in T}\left(E^{SUP}_{n,t} \cdot \hat{\lambda}^{buy}_{n,t} - E^{SUR}_{n,t} \cdot \hat{\lambda}^{sell}_{n,t} + \left(E^{PUR}_{n,t} - E^{SALE}_{n,t}\right) \cdot \hat{\lambda}^{p2p}_{t} + E^{SLC}_{n,t} \cdot \hat{\lambda}^{grid}_{t} + \sum_{s\in S} E^{B,D}_{n,s,t} \cdot \hat{\lambda}^{deg}_{n,s}\right) \quad (20)$$

D. Fixed AC without self-allocation

To avoid self-allocation of the energy injected into the grid for a member n, $\hat{\propto}_{n,m,t}$ is adjusted with (21) while also defining that allocation from one member to itself $\hat{\propto}_{n,n,t}$ is 0.

$$\hat{\propto}_{n,m,t} = \frac{\hat{\propto}^{init}_{n,t}}{1 - \hat{\propto}^{init}_{m,t}},\ \forall\ n, m \in N \quad (21)$$

Note that this still allow an injecting member to be allocated energy from others. Since implementing the constraints to guarantee that only consuming member have energy allocated to them (as regulated in some MS), would require significant changes in the initial model, this was left for future research. Still, the results from the fixed AC cases reveal interesting behaviours, as discussed in section III.

E. Strict Dynamic AC

The dynamic AC can be computed following any rule the CSC agrees. TABLE I. reviews several papers with proposals based on market criteria, fairness related methods or combinations of AC types. In this work, a market based dynamic AC is simulated [9], so that the local transactions determine the bilateral allocations $E^{ALC}_{n,m,t}$.

$$E^{ALC}_{n,m,t} = E^{PUR}_{n,m,t} - E^{SALE}_{n,m,t},\ \forall\ t \in T \quad (22)$$

where $E^{PUR}_{n,m,t}$ and $E^{SALE}_{n,m,t}$ are decision variables, representing the energy bought and sold bilaterally in the LEM, respectively. The pool market is enforced in all AC types using constraint (23) whose dual value is used as the LEM trade price.

$$\sum_{m\in N}\left(E^{PUR}_{n,m,t}\right) = \sum_{m\in N}\left(E^{SALE}_{n,m,t}\right),\ \forall\ t \in T \quad (23)$$

To find $E^{ALC}_{n,t}$, needed to compute $E^{SLC}_{n,t}$ in (14), the members injection into the grid $max\left(-E^{CMET}_{n,t}, 0\right)$ is added to the sum of all bilateral transactions with the other members in (24). This is necessary to stablish the members' ownership over the energy they inject into the grid, which can, then, be allocated to others through LEM sales.

$$E^{ALC}_{n,t} = max\left(-E^{CMET}_{n,t}, 0\right) - \sum_{m\in N} E^{SALE}_{n,m,t} - E^{PUR}_{n,m,t}, \forall n \in N \quad (24)$$

The bilateral dynamic AC values $\propto_{n,m,t}$ are found by using (22) in (25), and the pool-like AC $\propto_{n,t}$ are computed by using (24) in (26).

$$\propto_{n,m,t} = \frac{min\left(0, E^{ALC}_{n,m,t}\right)}{min\left(0, -E^{CMET}_{m,t}\right)},\ \forall\ t \in T \quad (25)$$

$$\propto_{n,t} = \frac{min\left(0, E^{ALC}_{n,t}\right)}{\sum_{m\in N} \max\left(-E^{MET}_{m,t}, 0\right)},\ \forall\ t \in T \quad (26)$$

To enforce the limits imposed by regulators in (18) the dynamic AC we call strict is used, and (27)–(29) are added.

$$E_{n,t}^{SALE} - E_{n,t}^{PUR} \leq -E_{n,t}^{CMET}, \forall\, t \in T \tag{27}$$

$$E_{n,t}^{SALE} \leq -E_{n,t}^{CMET},\ \forall\, t \in T \tag{28}$$

$$E_{n,t}^{PUR} \leq E_{n,t}^{CMET},\ \forall\, t \in T \tag{29}$$

F. Flexible Dynamic AC

The goal of flexible dynamic AC is to allow CSC members to use their SUP to locally share energy they do not inject into the grid. This can be done allowing negative ACs as described in [5], [16]. By removing constraints (27)–(29), members are no longer forced to sell internally at most what they inject into the grid, and ACs can take negative values or be bigger than 1. Although allocation is no longer attached to physical injection, this does not imply that the CSC members are sharing inexistant energy, since constraint (13) holds. Any excess $E_{n,t}^{PUR}$ or $E_{n,t}^{SALE}$ values not met by the members injections, given by negative $E_{n,t}^{CMET}$, are covered by trading with their SUP for $E_{n,t}^{SUP}$, or AGG for $E_{n,t}^{SUR}$. To avoid unlimited trading with the grid, a limit equal to each member's contracted power is imposed to $E_{n,t}^{SUP}$ and $E_{n,t}^{SUR}$.

III. Case Study

Case description

A CSC with 4 members is simulated. Their supply capacity, BESS and PV characteristics are given in TABLE II. Individual load and PV forecasts are based on data given in [18].

TABLE II. CSC members characterization

ID	Contracted Power	BESS				PV power
		Capacity	Max. power	SOC^{min}	SOC^{max}	
M1	3.45 kVA	------	------	------	------	------
M2	6.9 kVA	------	------	------	------	2.2 kWp
M3	6.9 kVA	6.4 kWh	2.0 kW	15%	95%	------
M4	10.35 kVA	13.5 kWh	5.0 kW	15%	95%	4.4 kWp

The prices at which the CSC members buy [19] and sell [20] energy, the grid access tariffs [21], and fixed ACs are given in TABLE III. Identical prices are assumed for all members except M4 (λ^{buy} = 0.12€/kWh) and M2 (λ^{sell} = 0.21 €/kWh, from 9h to 11h). These price differences are to create situations of arbitrage from buying from and selling to the grid. The stable prices in *t* for most members reduce the factors that can impact LEM trades and BESS scheduling. For the same reason, BESS are assumed to have no inefficiencies. Meanwhile, local peer-to-peer (P2P) transactions prices are set to the dual value (shadow price) of (23), as in [9].

TABLE III. CSC energy prices, tariffs and fixed AC

ID	λ^{buy}	λ^{sell}	λ^{grid}	Fixed AC
M1	0.1625 €/kWh	0.06 €/kWh	0.0106 €/kWh	0.10
M2	0.1625 €/kWh	0.06 €/kWh 0.21 €/kWh	0.0106 €/kWh	0.20
M3	0.1625 €/kWh	0.06 €/kWh	0.0106 €/kWh	0.30
M4	0.1200 €/kWh	0.06 €/kWh	0.0106 €/kWh	0.40

This study includes 5 scenarios, described in TABLE IV.

TABLE IV. Scenarios characterization

Scenario	Description
Stage1	– Each consumer operates independently from the others. – Consumers can only trade energy with their SUP/AGG (no LEM).
Fixed WSA	– Energy is allocated based on the initial fixed AC. – Members allocate energy to themselves. – Post-delivery LEM trade is determined by allocations.
Fixed NSA	– Energy is allocated based on an adjusted AC. – Self-allocation is avoided. – Post-delivery LEM trade is determined by allocations.
Dyn strict	– Allocations are determined by Post-delivery LEM trade. – ACs must be positive and sum up to 1.
Dyn flex	– Allocations are determined by Post-delivery LEM trade. – ACs can be positive or negative and sum up to 1.

Results

The individual costs for each member and the total costs for the whole CSC, in each scenario, are provided in Figure 2.

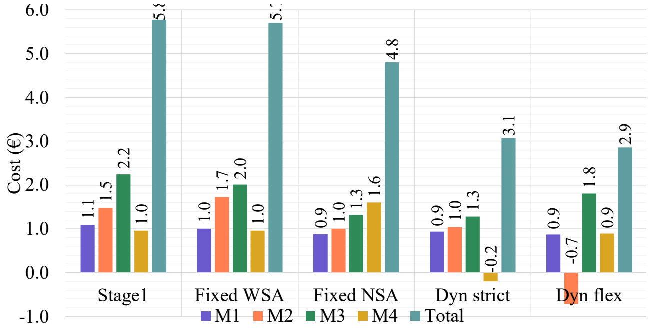

Figure 2. Individual and total daily costs in each scenario

Stage1 leads to the highest total daily cost, 5.8€, as there is no collective energy sharing, and individual surpluses are sold to the grid. In Fixed-WSA, costs drop marginally to 5.7€, mostly because the CSC members inject into the grid and self-allocate part of their energy, reducing the benefits of using BEES, i.e., to reduce $E_{n,t}^{SUP}$. Since there is no self-allocation in the Fixed-NSA, P2P trading from the BESS is more effective at reducing $E_{n,t}^{SUP}$ and total costs fall to 4.8€ (17% lower than in Stage1). With dynamic AC, LEM trades are not tied to predefined ACs values, and members have freedom to operate the BESS and trade locally. The benefits are therefore more substantial, with even certain members having profits (negative costs). In the Dyn-strict case, the total daily cost drops to 3.1€ (47% lower than in Stage1), and it drops even further in the Dyn-flex case, reaching 2.9€ (50% lower than in Stage1).

BESS have a significant role in the CSC, since they can physically increase the consumption from or the injection into the grid, in many cases leading to bilateral allocations and LEM trades. To further analyse the behaviour of the CSC members in these scenarios, Figure 3 and Figure 4 display the evolution of the SOC of M4's BESS.

M4's $\widehat{\propto}_{n,t}^{init}$ is very high (0.4), meaning that 40% of the energy it injects into the grid is self-allocated back in the Fixed WSA, becoming $E_{n,t}^{SUR}$ and sold back to the grid at a lower price. The only time it sells locally to other members is at 9h, to increase M2's surplus revenue. Note that M2 is already injecting into the grid due to its own PV generation and the CSC is allocating even more energy to it. Curiously, at 10h and 11h M4's SOC increase since M3, with 0.3 $\widehat{\propto}_{n,t}^{init}$, is injecting considerably into the grid to generate surplus for M2, however, 40% of this injection also goes to M4.

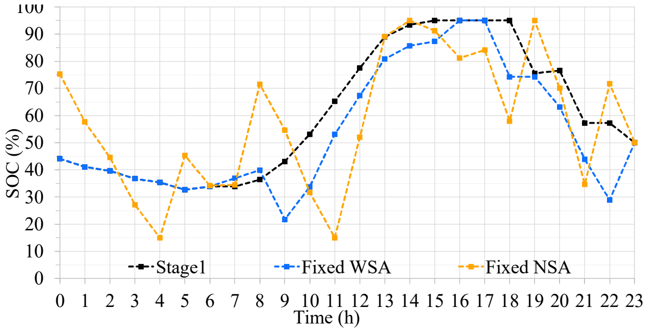

Figure 3. SOC of M4 BESS in Stage 1, Fixed WSA, and Fixed NSA

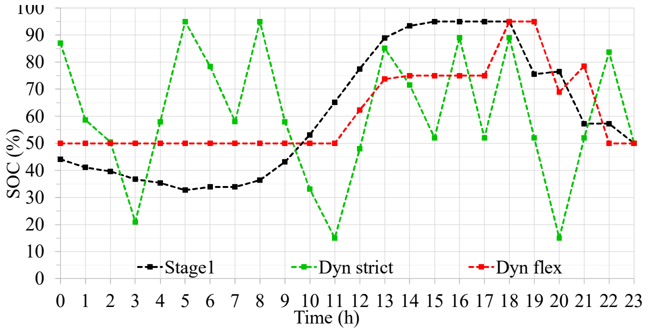

Figure 4. SOC of M4 BESS in Stage 1, Dyn strict, and Dyn flex

In the Fixed NSA scenario, the no self-allocation rule completely changes the BESS operation incentives. Now, M4's BESS generates surplus to M2, since is allocates more energy to it than M3 when injecting energy back to the grid. That is why M3's SOC reduces from 8h to 11h. In addition, this rule is more efficient and reduces considerably other members $E_{n,t}^{SUP}$, as seen in TABLE V. , and consequently their costs (Figure 2). There is also an up and down pattern that is very clear in the next Dynamic Strict scenario. Since M4 buys energy from the grid at a reduced price, it has an incentive to arbitrage, obtaining gains from selling to others who avoid consuming at a higher cost.

TABLE V. EC TRADES WITH EACH AC TYPE

Scenarios	M	Esup [kWh]	Esur [kWh]	Epur [kWh]	Esale [kWh]
Stage1	M1	6.69	0	------	------
	M2	11.86	3.31	------	------
	M3	13.85	0	------	------
	M4	8.52	1.10	------	------
Fixed WSA	M1	6.02	0	0.67	0
	M2	11.86	1.34	0.67	2.65
	M3	11.84	0	2.00	0
	M4	9.56	1.45	1.33	2.02
Fixed NSA	M1	2.52	1.53	5.69	0
	M2	5.37	4.07	10.56	3.31
	M3	0	0	16.11	2.26
	M4	35.03	0.82	2.95	29.74
Dyn strict	M1	1.23	0.00	6.26	0.80
	M2	1.18	20.55	29.58	1.67
	M3	0.44	0	23.05	9.65
	M4	54.19	0	0	46.78
Dyn flex	M1	0	0	6.69	0
	M2	0	20.70	30.91	1.67
	M3	0	0	13.85	0
	M4	57.20	0	0	49.78

However, in the Fixed WSA, Fixed NSA, and Dyn strict cases, constraints (27)–(29) are active and the only way to arbitrage is by physically consuming and injecting through the BESS, as it is clearly visible in the Dyn strict SOC. Arbitrage takes place during the whole set T, and not only between 9h and 11h. This work supposes zero BESS losses to increase this effect, but intertemporal arbitrage is unavoidable if members have sufficiently different SUP prices in an CSC, even for fixed AC. Using BESS to physically arbitrage in a non-intertemporal problem leads to waste of energy and asset degradation. In the Dyn flex, where constraints (27)–(29) are supressed, M3 and M4's BESS are constant. Since members can trade without physical leverage, BESS are only needed to make use of the total CSC surplus, saving it to reduce CSC consumption after the sun has set. TABLE V. shows how arbitrage significantly increases from Fixed WSA to Fixed NSA and it is even more present in the Dyn strict and the Dyn flex, i.e., M4 buys from its SUP ($E_{n,t}^{SUP}$) to sell to M2 so it can sell to the grid ($E_{n,t}^{SUR}$).

IV. CONCLUSION

This work simulates a CSC under different energy sharing rules to assess how fixed and dynamic ACs impact members' behaviour and the operation of the BESS. Among the key findings are:

- AC types and their variants significantly impact CSC costs, allocation, and dispatch.
- Dynamic AC provides lower costs than fixed AC.
- Arbitrage in CSC with BESS is inevitable since members have unique price signals from their contracted SUP and AGG.
- AC types that force allocation attached to physical deliveries originate ups and downs of BESS SOC, which generates losses.
- These losses are minimized if flexible dynamic ACs are allowed, letting members trade internally energy non-attached to physical deliveries.

Regulators should consider these findings when setting CSC AC rules, especially the limits to apply on the non-physical trade with the grid, should the flexible dynamic ACs be allowed.

Finally, since a limited number of AC variants is simulated, future research shall include more fixed and proportional AC variants as well as propose more innovative dynamic cases. Other criteria can also be explored to assess the collective and individual CSC outcomes of different types of ACs, including demand response, additional resource technologies, and more realistic case studies. This paper has focused on exposing the impact of AC types on CSC scheduling, so the simulated scenarios have been limited to show these effects.

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APPENDIX

TABLE I. REVIEW OF RECENT PUBLICATIONS ON THE SIMULATION OF CSC ALLOCATION APPROACHES

Ref.	Reviewed aspects				
	Country	**Asset types**	**AC types**	**Regulatory recommendations**	**Post-delivery LEM**
[22]	Italy, 2023	Fixed load, PV, BESS.	N/A. Virtual allocation	No.	No.
[7]	France, 2022	Fixed Load, PV, EV, BESS	Fixed, proportional and dynamic.	No.	No.
[23]	Finland, 2022	Fixed load, PV.	Proportional	No.	No.
[14]	39 countries, 2023	Fixed load, PV.	Proportional	Yes.	No.
[24]	Spain, 2023	Fixed load, PV.	Fixed, proportional and dynamic.	No.	No.
[10]	Austria, 2023	Fixed load, PV.	Fixed.	No.	Yes, coupled with the allocations using fixed AC.
[12]	Not defined, 2022	Fixed load, PV.	Dynamic.	No.	Yes, pool trades with Dynamic AC.
[11]	France, 2023	Fixed load, PV.	Proportional and dynamic.	No.	Yes, pool trades.
[13]	Portugal	Flex load, PV, BESS,	Dynamic.	No.	Yes, pool trades with Dynamic AC.
[8]	Spain, 2023	Flex load, PV, BESS, Conventional gen.	Fixed, proportional to contracted power, proportional do consumption, dynamic.	Yes. Proportional AC proposed. Dynamic is deemed too complex, although not clear why.	No.
[15]	Spain, 2023	Fixed load, PV.	Yes, fixed, proportional to contracted power, proportional to consumption.	Yes, proportional AC proposed.	No.