Quantifying CO2 Emissions from Operational Strategies in Collective Self-Consumption based Energy Communities

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Abstract:
Collective Self-Consumption (CSC) energy communities are rapidly expanding across Europe, thanks to the deployment of solar power systems and regulatory frameworks that allow energy to be shared among multiple members. Although most operational studies emphasize economic performance and self-consumption, the environmental implications of daily community management are still not assessed with the same consistency or comparability. This gap is particularly evident when contrasting alternative allocation and flexibility strategies under accounting rules that must remain compliant with CSC schemes. In practice, operational choices can substantially change the timing and volume of electricity imported from the grid, and these changes directly determine the operational CO2 emissions attributable to community operation. This paper presents an operationally grounded and CSC compliant methodology intended to quantify CO2 emissions attributable to energy community operation under alternative management strategies. The method relies on an hourly energy flow decomposition that assigns each member's electricity consumption to its supply origin, distinguishing national grid imports, locally produced photovoltaic energy, and energy discharged from a community energy storage system, while ensuring that allocations follow collective self-consumption accounting rules. The resulting energy traces are then translated into emissions through intensity factors expressed in grams of CO2 per kilowatt hour, enabling the computation of total strategy attributable CO2 emissions as well as avoided emissions relative to a reference operation. The methodology is demonstrated employing a real energy community in Barcelona composed of public buildings with measured consumption and photovoltaic generation. We compare the nominal as currently operated baseline characterized by static allocation rules, an optimized operation obtained through centralized Mixed-Integer Linear or Quadratic Programming formulations that coordinate time varying allocation coefficients and storage scheduling subject to regulatory constraints, and data-driven strategies that predict dynamic allocation coefficients from historical operation and contextual features. For each strategy, we report total operational CO2 emissions and CO2 avoided relative to the nominal baseline, along with self-consumption, surplus exports, and grid import dependency to contextualize outcomes. Emissions intensity in grams of CO2 per kilowatt hour is included to interpret temporal shifting in grid exchanges. Results show that dynamic allocation and storage scheduling reshape the timing and volume of grid imports, producing measurable differences in attributable CO2 emissions while maintaining regulation compliant energy distribution.

Keywords:
CO2 emissions, energy communities, data-driven energy management, collective self-consumption, environmental impact.

1. Introduction

Energy communities have emerged across Europe as a relevant organizational and operational mechanism to accelerate the deployment of distributed renewable ewnergy generation, enhance local energy autonomy, and support decarbonization objectives under increasingly participatory electricity market structures. Their development is strongly aligned with the broader European energy transition agenda, in which collective action, demand-side coordination, and shared access to renewable resources are viewed as key enablers of a low-carbon and socially inclusive energy system [1]. In this context, the environmental value of local renewable integration is widely recognized, and a growing body of research has shown that properly designed and coordinated community-scale systems can reduce dependence on conventional grid electricity and contribute to lower CO2 emissions [2]. Additional evidence has confirmed the environmental and economic relevance of community-based energy schemes under different European operating conditions [3]. Other studies have shown that the environmental performance of community energy systems is also highly influenced by the CO2 footprint of the supplying grid and by the optimal configuration of local assets [4]. From a broader sustainability perspective, the reduction of CO2 emissions through increased renewable energy utilization remains a central pillar of current decarbonization strategies [5]. Beyond the general concept of energy communities, recent research has increasingly examined how technology choices, flexibility assets, and operational coordination affect energy, economic, and environmental performance. Prior work has shown that the integration of storage and coordinated control may influence both grid exchanges and the resulting carbon footprint of community operation [6]. Related studies have also highlighted that forecast quality and data-driven energy management strategies can significantly affect the emissions performance of smart residential systems [7]. In addition, integrated optimization approaches have shown that combining energy generation, storage, and demand-side flexibility can improve economic and environmental outcomes in energy communities [8]. Other contributions have further demonstrated that the deployment of different technologies within a community can reshape energy flows, reduce grid feed-in, and lower associated emissions [9]. At the same time, the implementation of energy communities in practice still faces important regulatory, technical, and data-management challenges, particularly when advanced digital services and intelligent operational schemes are introduced. These limitations become especially relevant when environmental assessment is expected to reflect real operational behavior rather than static [10].

Within the European regulatory context, Collective Self-Consumption (CSC) has emerged as a key scheme for enabling local energy sharing among users connected to the same low-voltage network, allowing electricity from shared photovoltaic systems to be distributed according to predefined allocation rules; however, its performance depends strongly on the allocation logic adopted, since dynamic sharing keys and alternative allocation algorithms can significantly modify energy distribution, profitability, self-sufficiency, and the effective use of shared electricity, while static coefficients, as commonly applied in Spain, offer simplicity but may limit the economic use of locally generated energy [11], [12]. Although the literature has widely examined CSC from techno-economic and regulatory perspectives, the environmental consequences of daily operational decisions remain less consistently quantified: while prior studies show that CSC can reduce carbon emissions under appropriate conditions [13], and that optimized coordination and flexibility management can improve environmental performance and alter system-level emissions [6], [8], there is still a lack of transparent, comparable, and regulation-compliant methodologies that directly attribute CO2 emissions to alternative community management and allocation strategies within CSC energy communities. This gap is particularly important because operational strategies directly affect the temporal profile and magnitude of electricity imported from the grid. Even when identical demand and photovoltaic generation profiles are considered, different allocation rules and flexibility decisions can lead to substantially different patterns of local renewable use, storage utilization, surplus export, and external grid dependence. Since operational CO2 emissions are closely related to the source of the energy serving community demand, the environmental performance of a CSC scheme cannot be fully understood without tracing how energy is allocated and consumed under each strategy. This is especially relevant in communities where dynamic allocation approaches are increasingly being explored through algorithmic, optimization-based, or data-driven methods [14]. It is also consistent with simulation evidence showing that the design of allocation coefficients can significantly affect operational outcomes at community level [15].

In response to this need, this paper proposes a CSC-compliant methodology to quantify CO2 emissions attributable to energy community operation under alternative management strategies. The approach is based on an hourly energy flow decomposition that distinguishes national grid imports, locally produced photovoltaic energy, and energy discharged from a Community Energy Storage System (CESS), which are then translated into emissions using source-specific intensity factors. Four operating cases are compared: a full grid-dependent reference, a nominal baseline with static allocation coefficients, a machine-learning-based dynamic allocation strategy, and an optimized strategy derived from Mixed-Integer Linear Programming (MILP) or Mixed-Integer Quadratic Programming (MIQP) formulations. The methodology is tested on a real energy community in Barcelona, showing that energy allocation and storage decisions can significantly affect the community's carbon footprint.

1.1 Contributions

The main contributions of this work are as follows:

1. A Collective Self-Consumption compliant CO2 emissions accounting methodology is proposed, based on hourly source-resolved energy flow decomposition that attributes electricity consumption to grid imports, locally generated photovoltaic energy, and discharged storage energy.
2. A comparative environmental assessment framework is developed to evaluate four operational cases, including a full grid-dependent reference, a static baseline, a machine learning-based dynamic allocation strategy, and an optimization-based dynamic allocation strategy under consistent accounting assumptions.
3. A real case study in Barcelona is used to demonstrate that allocation and storage operation strategies can significantly modify grid import patterns and therefore produce measurable differences in attributable operational CO2 emissions.

The remainder of the paper is organized as follows. Section 2 presents the general problem context. Section 3 describes the proposed CO2 emissions quantification methodology and some of the different indices for performance assessment. Section 4 presents the compared allocation strategies. Section 5 discusses the results obtained for the Barcelona energy community. Finally, Section 6 summarizes the main conclusions and outlines future research directions.

2. Problem Statement and Case Study

This work addresses the need to quantify how different operational strategies in CSC energy communities affect attributable operational CO2 emissions, beyond the usual techno-economic evaluation. The comparison is performed on the same community under identical demand, PV generation, storage characteristics, and emissions factors, so that any differences in emissions can be attributed solely to the operating logic used to allocate local energy and manage flexibility.

2.1 Collective Self-Consumption Context

The CSC scheme is a key framework for local energy sharing in countries such as Spain. It allows multiple consumers to use electricity from a shared PV installation, with operation based on local generation, grid exchanges, and, when available, a CESS. In the Spanish CSC framework, the core operational mechanism is the set of allocation coefficients that determines how the net generated energy is assigned among consumers. The basis of the CSC scheme resides in the equation of the individualized net energy produced for each member in the community, assume the energy community is composed for N members so the individual net energy assigned to the member n at time t will be given by the next relation:

$$INE_n(t) = \beta_n(t) \cdot TEG(t), \qquad \forall n \epsilon N \qquad (1)$$

In where $TEG(t)$ is the total energy generated by the community at time instant t and $\beta_n(t)$ is the allocation coefficient corresponding to the member n which corresponds to the portion of the energy that is shared with this member. These coefficients must be agreed by all participants and, for every hour of the billing period, their sum across all consumers must be equal to one. Also, these allocation coefficients need to comply the following constraint:

$$\sum_{n=1}^{N} \beta_n(t) = 1 \qquad (2)$$

Which, in simple words, constrains the produced energy inside of the community to be shared in its entirety across the members of the energy community. From an operational standpoint, these coefficients directly determine how much locally generated energy is assigned to each member and therefore condition the resulting balance between local renewable use, surplus energy, and grid dependence.

This regulatory structure is particularly relevant to the present study because allocation decisions influence the environmental performance of CSC communities. Changes in allocation coefficients and storage scheduling affect the balance between locally consumed photovoltaic energy and electricity imported from the grid, thereby modifying the associated operational CO2 emissions. As a result, different operational strategies applied to the same community may yield different environmental outcomes. Accordingly, the comparative assessment adopted in this work is grounded in a regulatory-consistent framework that captures how operational decisions shape the balance between local renewable utilization and grid dependence.

2.2 Case Study Description

The proposed methodology is demonstrated using a real Municipal Energy Community located in the province of Barcelona, Spain. The case study is particularly relevant because it represents practical CSC implementation based on public infrastructure, real measured data, and realistic operational conditions. As such, it provides a suitable benchmark for evaluating how alternative community management strategies affect attributable operational CO2 emissions under an actual regulatory and technical setting. In addition, the case reflects a type of community that is increasingly representative of local energy transition initiatives in Europe, where municipalities play an active role in promoting shared renewable generation and coordinated energy use among public and community-oriented assets.

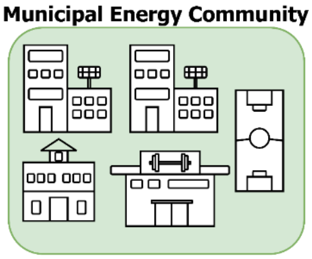

Figure 1. *Simplified schematic representation of the Municipal Energy Community case study in Barcelona.*

Table 1. *Summary of evaluated scenarios and considered operational elements.*

Scenario	*Description*	*Shared PV*	*Dynamic allocation*	*Community grid imports*	*Market exports*	*CESS*
S1	Full grid dependence	✗	✗	✓	✗	✗
S2	Nominal CSC baseline	✓	✗	✓	✗	✗
S3	XGBoost dynamic allocation	✓	✓	✓	✓	✗
S4	MILP optimization-based allocation	✓	✓	✓	✓	✓

At the system level, the community is composed of five public buildings with different demand profiles and functional roles, namely two school buildings, a sports center, a sports area, and a civic center. Shared photovoltaic generation is available within the community and is associated with participating buildings according to the CSC scheme adopted in the study. The community may also include a Community Energy Storage System to provide additional flexibility by temporally shifting locally available energy and reducing dependence on external grid imports. A simplified schematic representation of the Municipal Energy Community is shown in Fig. 1, where the participating buildings and the shared-community structure are illustrated at conceptual level.

The analysis is based on one year of measured electricity consumption and photovoltaic generation data collected for the community at hourly resolution. For the comparative assessment presented in this paper, a representative week of operation is selected as the main analysis horizon in order to provide a clear and realistic view of the behavior of the evaluated strategies.

2.3 Evaluation Scenarios

To assess how alternative operational decisions affect the environmental performance of case study, four scenarios are evaluated under a common technical and regulatory basis. The first scenario is a full grid-dependent reference in which all electricity demand is supplied by the national grid, providing a counterfactual benchmark without local photovoltaic contribution or storage support. The second scenario represents the nominal operation of the Municipal Energy Community under the current CSC arrangement, where locally generated photovoltaic energy is distributed using nominal static allocation coefficients. The third scenario considers a dynamic allocation strategy based on eXtreme Gradient Boosting (XGBoost) predictions, while the fourth scenario adopts a dynamic allocation strategy derived from a centralized Mixed-Integer Linear Programming framework, including storage scheduling when applicable. Together, these scenarios enable a comparison ranging from a non-coordinated reference condition to progressively more advanced forms of community operation.

The comparison is conducted primarily at the community level to evaluate how each scenario affects total operational CO2 emissions and the overall dependence on local renewable generation, storage support, and grid imports. When relevant, the assessment is also extended to the member level to examine how the environmental effect of each strategy is distributed among participants with different demand profiles and roles within the community. Table 1 summarizes the evaluated scenarios and their main operational elements. By keeping the physical configuration and input data unchanged across all cases, the analysis isolates the impact of community operation as the main source of differences in attributable CO2 emissions. The next section presents the methodology used to quantify and compare these emissions under the evaluated scenarios.

3. Methodology for CO2 Emissions Quantification

The proposed framework adopts an attributional, source-based approach to quantify the operational CO2 emissions of CSC energy communities according to the origin of the electricity used to meet demand. By distinguishing among grid imports, shared photovoltaic generation, and electricity supplied by the CESS, the methodology captures the different carbon intensities associated with each source. This decomposition provides a consistent basis for attributing emissions and for comparing the environmental performance of alternative community operating strategies.

3.1 Source Emissions Factors

To translate the traced energy flows into attributable CO2 emissions, a source-specific emissions factor is assigned to each electricity supply source considered in the study [16]. In accordance with the source-based accounting framework described above, three factors are defined, corresponding to electricity imported from the national grid, electricity supplied directly by the shared photovoltaic installation, and electricity delivered by the Community Energy Storage System. These factors are expressed in grams of CO2 per kilowatt hour and represent the carbon intensity associated with each source under the adopted accounting assumptions.

Table 2. *Source-specific emissions factors adopted in the study [16].*

Energy Source	Symbol	Value	Unit
National Grid Energy	γ^g	190	gCO2/kWh
Photovoltaic Energy	γ^p	20	gCO2/kWh
CESS	γ^c	60	gCO2/kWh

The source-specific emissions factors, adopted from [16], are reported in Table 2 and are kept constant across all evaluated scenarios. Therefore, any difference in total operational CO2 emissions between scenarios is attributable exclusively to changes in the source composition of the energy used to satisfy demand, which in turn are driven by the adopted operational strategy rather than by variations in the emissions parameters themselves.

3.2 Operational CO2 Emissions Model and Indices

Based on the source-based accounting framework introduced above, the operational CO2 emissions of the community are quantified from the amount of electricity supplied by each considered source at every time step. Let $E_g(t)$, $E_p(t)$ and $E_c(t)$ denote, respectively, the electricity supplied at hour t by the national grid, the shared photovoltaic system, and the CESS. Using the source-specific emissions factors γ^g, γ^p and γ^c the total operational CO2 emissions of the community can be computed at time t as:

$$TE(t) = E_g(t)\gamma^g + E_p(t)\gamma^p + E_c(t)\gamma^c \qquad (3)$$

The community operational CO2 emissions over the analysis horizon T are obtained from:

$$CTE = \sum_{t \in T} TE(t) \qquad (4)$$

When a member-level assessment is required, the same formulation can be applied individually to each participant i. In that case, the hourly attributable emissions are expressed as:

$$TE_n(t) = E_g^n(t)\gamma^g + E_p^n(t)\gamma^p + E_c^n(t)\gamma^c \qquad (5)$$

In the same way, the equivalent of Eq. 4 can be obtained for a member level emission evaluation:

$$MTE = \sum_{t \in T} TE_n(t) \qquad (6)$$

Based on these expressions, several emissions-based performance indices are defined to support the comparative assessment of the evaluated scenarios. The primary environmental indicator is the total operational CO2 emissions CTE. In addition, the avoided CO2 emissions of a given case with respect to a reference scenario are computed as:

$$ATE = CTE^{ref} - CTE^{case} \qquad (7)$$

Where TE^{ref} denotes the total operational emissions of the selected reference case and TE^{case} corresponds to the total emissions of the evaluated case. To complement the absolute emissions results, an emissions intensity factor is also considered. This metric expresses the operational CO2 emissions per unit of energy demand served over the analysis horizon and is defined as:

$$IF = \frac{CTE}{\sum_{t \in T} E_L(t)} \qquad (8)$$

Where $E_L(t)$ represents the total electricity demand of the community at hour t. This indicator, expressed in gCO2/kWh, is useful for interpreting how alternative operational strategies modify the carbon intensity of the electricity effectively consumed by the community. Together, these equations and indices provide the analytical basis for comparing the environmental performance of the considered CSC operating scenarios.

3.3 Complementary Operational Indicators

To support the interpretation of the emissions results, three complementary operational indicators are considered. The first one is Self-Consumption, $SC(t)$, which quantifies the amount of locally allocated photovoltaic energy that is effectively absorbed by the community demand at time t and it's defined as:

$$SC(t) = \sum_{n \in N} \min\left[E_p^n(t), E_L^n(t)\right] \tag{9}$$

Where $E_p^n(t)$ denotes the electricity supplied by the shared photovoltaic system at time t, and $E_L^n(t)$ is the total electricity demand of the community at the same instant. This indicator represents the instantaneous photovoltaic energy effectively used within the community. The second indicator is Energy Surplus, which quantifies the amount of locally generated photovoltaic energy that is not absorbed by the community demand and is therefore exported to the external grid at time t, it is defined as:

$$ES(t) = \sum_{n \in N} \max\,[E_p^n(t) - E_L^n(t), 0] \tag{10}$$

Thus, $ES(t)$ represents the instantaneous photovoltaic surplus injected into the external grid. Finally, the Grid Import Dependency measures the portion of the community demand that must be supplied by the national grid at time t. It can be expressed as:

$$GID_n(t) = \frac{E_g^n(t)}{E_L^n(t)} \tag{11}$$

This indicator reflects the community's real-time reliance on external electricity supply, while the full set of indicators explains how each strategy changes the balance between local PV use, surplus export, and grid dependence. Overall, the methodology provides a consistent way to convert traced energy flows into operational CO2 emissions and related performance metrics, forming the basis for the evaluation of the operational strategies in the next section.

4. Operational Strategies Under Evaluation

4.1 Full Grid-Dependent Reference

The full grid-dependent reference represents a counterfactual scenario in which the electricity demand of the community is entirely supplied by the national grid. In this case, no locally generated photovoltaic energy is allocated to the community members, and the CESS is not used. Accordingly, the community operates as if no CSC arrangement were in place, and all demand is covered exclusively through external grid imports. This scenario is included to provide an upper benchmark for operational CO2 emissions, since it reflects the condition of maximum dependence on the external power system and the absence of local renewable utilization or storage-based flexibility.

4.2 Nominal CSC Baseline with Static Allocation Coefficients

The nominal CSC baseline corresponds to the current operation of the MEC under the Spanish CSC framework. In this case, the photovoltaic energy generated within the community is distributed among the members using fixed allocation coefficients that remain constant over the entire analysis horizon. These coefficients define the fraction of the generation associated with each prosumer that is assigned to the participating members and therefore determine the baseline pattern of local renewable utilization under the existing operating arrangement.

Table 3. *Nominal static allocation coefficients of the Municipal Energy Community.*

Members	Prosumer 1 [%]	Prosumer 2 [%]
Prosumer 1	30.00	0.00
Prosumer 2	0.00	98.78
Consumer 1	48.17	0.00
Consumer 2	0.00	1.22
Consumer 3	21.83	0.00

In the studied community, Prosumer 1 and Prosumer 2 correspond to the two school buildings, which are the members equipped with photovoltaic generation assets. The static allocation coefficients adopted in the nominal case are reported in Table 3. As shown, the photovoltaic generation of each school building is distributed among the community members according to a predefined percentage structure, which reflects the current CSC agreement. Under this scheme, the allocated photovoltaic energy varies in absolute value with the available generation at each time step, while the allocation proportions remain unchanged. This scenario is therefore used as the reference representation of the actual community operation against which the dynamic strategies are compared.

4.3 XGBoost-based Dynamic Allocation Strategy

The XGBoost-based dynamic allocation strategy replaces the fixed coefficients of the nominal CSC baseline with time-varying allocation coefficients predicted from data. In this case, the allocation process follows the ideal dynamic allocation algorithm developed in [14], where the coefficients are computed at each time step using XGBoost models trained from historical operation and contextual information. In this way, the allocation of shared photovoltaic energy is adapted to the expected operating conditions of the community instead of remaining fixed over the entire horizon.

From an operational perspective, this strategy preserves the same CSC structure as the nominal case but introduces temporal adaptability in the allocation coefficients. Therefore, the amount of photovoltaic energy assigned to each member changes not only with the available generation, but also with the predicted allocation pattern provided by the XGBoost-based model. This scenario is included to evaluate whether a data-driven and computationally efficient dynamic allocation approach can improve the environmental performance of the community with respect to the nominal static baseline.

4.4 MILP-based Dynamic Allocation Strategy

The MILP-based dynamic allocation strategy computes time-varying allocation coefficients through a centralized optimization framework that coordinates the distribution of shared photovoltaic energy and, when enabled, the operation of the CESS. Unlike the nominal baseline, where the allocation coefficients remain fixed, this strategy updates the allocation pattern at each time step to improve community operation under the adopted CSC constraints. In this work, the optimization problem is formulated as a MILP model whose decision variables include the dynamic allocation coefficients and the main storage operation variables, with an objective function that jointly seeks to reduce community energy surplus and enhance self-consumption based on the dynamic models defined in [17]. A compact representation can be written as:

$$min_{\beta(t),u(t)} \sum_{t\in T} \psi[ES(t), SC(t), u(t)] \qquad (12)$$

subject to the corresponding CSC allocation rules, energy balance equations, storage dynamics, and operational bounds. In this formulation, $\beta(t)$ denotes the allocation coefficient associated with prosumer p and member n at time t, while $u(t)$ groups the additional storage operation decisions. In general, optimization is constrained by the coefficient consistency conditions, the admissible bounds on the allocation variables, the community energy balance, and the dynamic and physical limits of the CESS. Therefore, this strategy provides a coordinated benchmark representing the most structured and adaptive form of community operation considered in the present study, as it combines dynamic photovoltaic allocation with storage-assisted temporal flexibility. In summary, the four evaluated strategies range from a counterfactual condition of full grid dependence to progressively more coordinated forms of CSC operation. The nominal baseline represents the current static allocation practice, whereas the XGBoost-based and MILP-based strategies introduce dynamic allocation through data-driven and optimization-based decision mechanisms, respectively. This set of scenarios enables a consistent comparison of how increasing levels of operational intelligence and coordination influence the environmental performance of the community. The results of this comparison are presented and discussed in the following section.

5. Results and Discussion

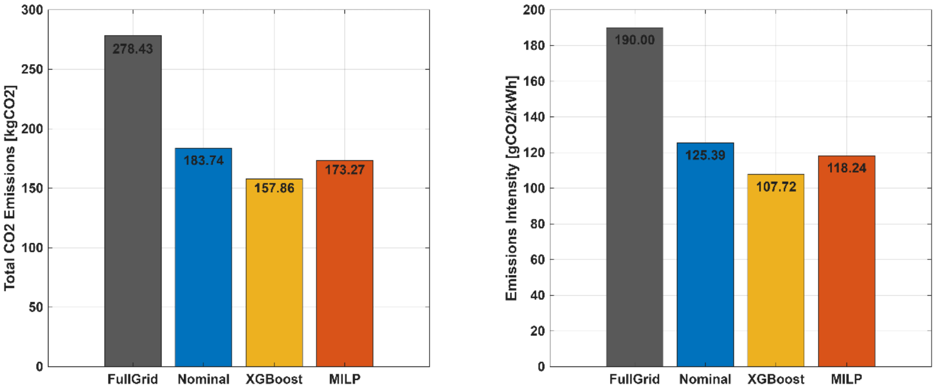

Figure 2. *Total CO2 emissions and emissions intensity for the evaluated scenarios.*

This section presents the comparative environmental assessment of the four operating scenarios over the selected analysis week. The discussion is based on the main CO2 indicators and complementary operational metrics introduced in Section 3, with the aim of evaluating how each strategy modifies the electricity source mix and, consequently, the attributable operational CO2 emissions. Fig. 2 compares total operational CO2 emissions and emissions intensity for the four scenarios. As expected, the full grid-dependent reference exhibits the highest impact, with 278.43 kgCO2 and 190.00 gCO2/kWh, since all demand is supplied by the national grid. The nominal CSC baseline already reduces emissions to 183.74 kgCO2 and 125.39 gCO2/kWh, corresponding to a 34.01% reduction relative to Full Grid case. Among the dynamic strategies, the XGBoost-based allocation achieves the best environmental performance, with 157.86 kgCO2 and 107.72 gCO2/kWh, while the MILP-based strategy reaches 173.27 kgCO2 and 118.24 gCO2/kWh. Therefore, both dynamic approaches improve the nominal baseline, but the XGBoost strategy provides the largest weekly reduction in both total emissions and emissions intensity.

Table 3. *Complementary operational indicators for the CSC-based scenarios.*

Scenario	CTE [kgCO2]	IF [gCO2/kWh]	ATE [kgCO2]
Full Grid	278.43	190.00	0.00
Nominal	183.74	125.39	94.69
XGBoost	157.86	107.72	120.57
MILP	173.27	118.24	105.16

The avoided CO2 emissions shown in Fig. 3 confirm that all CSC-based scenarios deliver a relevant environmental benefit with respect to the full grid-dependent case, with XGBoost achieving the highest weekly avoided emissions, followed by MILP and then the nominal baseline. This ranking is also reflected in the cumulative emissions profiles in Fig. 4, where the curves separate progressively over the week, indicating that the environmental advantage of the dynamic strategies is not concentrated in isolated hours but accumulates consistently over time. The XGBoost case remains below the other scenarios for most of the horizon, while the MILP profile stays below the nominal baseline but above XGBoost, confirming the robustness of the weekly comparison.

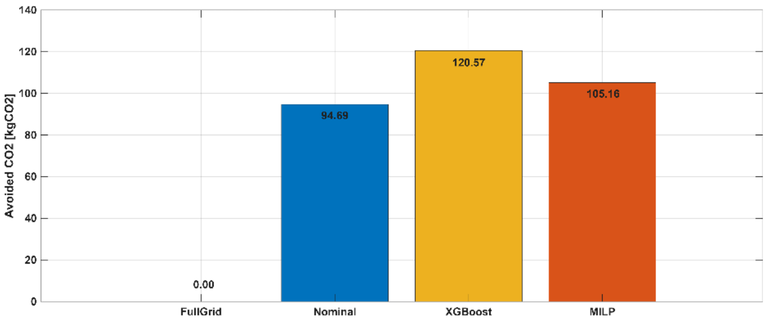

Figure 3. *Avoided CO2 emissions relative to reference scenario.*

The complementary operational indicators shown in Fig. 5 help to explain the previous results. The XGBoost-based strategy achieves the highest self-consumption, equal to 785.35 kWh, and the lowest mean grid import dependency, equal to 0.548, which explains its superior CO2 performance. The nominal baseline shows lower self-consumption and the highest surplus, indicating that static coefficients are less effective at adapting local photovoltaic use to the demand profile. By contrast, the MILP-based strategy achieves by far the lowest surplus, 202.96 kWh, but not the lowest emissions, since its self-consumption remains below XGBoost and its grid dependency stays relatively high. This confirms that reducing surplus and minimizing CO2 emissions are related but not equivalent objectives.

Table 4. *Member-level total operational emissions for the selected week.*

Member	Nominal [kgCO2]	XGBoost [kgCO2]	MILP [kgCO2]
School E	37.08	35.52	35.89
School P	48.58	47.74	48.44
Sports Center	4.56	0.27	1.55
Sports Area	76.47	69.99	76.25
Civic Center	17.06	4.33	11.15

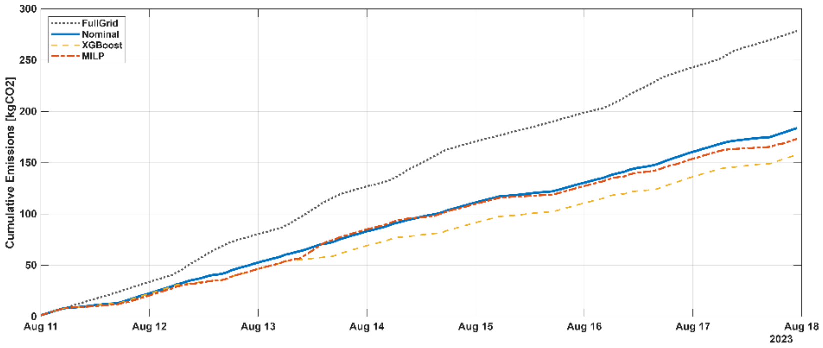

Figure 4. *Cumulative CO2 emissions over the selected analysis week.*

The member-level emissions reported in Table 3 show that the XGBoost-based strategy yields the lowest emissions for all five buildings during the selected week, with particularly strong reductions for the Sports

Center and the Civic Center. The MILP-based strategy also improves the nominal baseline in most cases, but its gains are smaller and more uneven, remaining relatively close to the nominal values for the two school buildings and the Sports Area. These results support the community-level findings and suggest that the XGBoost strategy is more effective at reallocating local photovoltaic energy toward members whose demand can absorb it with greater environmental benefit, whereas the MILP strategy is primarily more effective at limiting surplus.

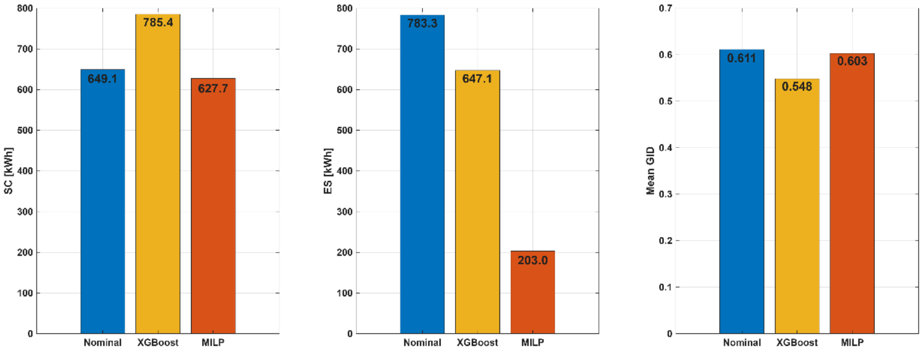

Figure 5. *SC, ES, and mean GID indices for the CSC-based scenarios.*

5.5 Main Findings and Implications

The results show that the operation of a CSC energy community has a direct impact on its attributable operational CO2 emissions. While any CSC-based arrangement already provides a clear environmental benefit relative to full grid dependence, dynamic allocation strategies further improve performance beyond the nominal static baseline. In the analyzed week, the XGBoost-based strategy achieved the best CO2 performance, whereas the MILP-based strategy was more effective at reducing surplus, confirming that different operational objectives can lead to different environmental outcomes.

6. Conclusions and Future Work

This paper proposed a source-resolved methodology to quantify operational CO2 emissions in CSC energy communities and applied it to a real Municipal Energy Community in Barcelona. The results showed that all CSC-based strategies reduce emissions relative to full grid dependence, while dynamic allocation further improves environmental performance. In the analyzed week, the XGBoost-based strategy achieved the lowest CO2 emissions, whereas the MILP-based strategy was especially effective at reducing surplus energy. Overall, the findings highlight that the carbon footprint of an energy community depends not only on its assets but also on how local energy is allocated and managed.

Acknowledgments

This work has received support from the Spanish Government under MICINN projects PID2024-156522OB-C33 co-funded with the European Union ERDF funds, OPEN4CEC PCI2023-145975-2 and SMART-LEM PCI2023-145977-2 funded by grant MCIU/AEI/10.13039/501100011033 and co-funded by European Union.

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