Local Renewable Energy Community: Peer-to-Peer Trading and Dynamic Sharing versus Traditional Tariffs

(Article begins on next page)

Local Renewable Energy Community: Peer-to-Peer Trading and Dynamic Sharing versus Traditional Tariffs

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***Abstract*—Renewable Energy Communities (RECs) can enhance local renewable utilization and reduce energy costs, particularly in rural and weak-grid areas. However, REC performance strongly depends on energy sharing rules and their interaction with tariffs, peer-to-peer (P2P) trading, and network constraints. This paper proposes an optimization-based framework to compare alternative energy sharing approaches—constant, net-consumption-based, and hybrid dynamic sharing—within a rural REC. A mixed-integer linear programming model is formulated to maximize REC profit, ensuring local P2P energy sharing, and dynamic sharing between the members. The framework is demonstrated on a Portuguese rural REC case study. Results show that time-of-use pricing alone reduced REC profit by 33.4%, whereas enabling P2P trading improved local matching and increased profit by 9.0%, while net-consumption-based sharing achieved the best technical performance by minimizing grid imports and exports and increasing shared energy by 62.7% relative to constant coefficients.**

***Index Terms*—Dynamic sharing, energy tariffs, peer-to-peer, renewable energy communities, rural areas**

I. Introduction

Renewable Energy Communities (RECs) have become an important organizational model for promoting local renewable generation, increasing self-consumption, and strengthening citizen participation in the energy transition [1], [2]. Their potential is particularly relevant in rural and weak-grid areas, where distribution infrastructures are more vulnerable to voltage deviations, congestion, and service quality problems, while simultaneously offering significant untapped potential for distributed photovoltaic (PV) generation and flexible demand [3]. In such contexts, RECs can support both local decarbonization and improved use of distributed energy resources (DERs). Reported results confirm these benefits, with Fonseca *et al.* [4] showing average cost reductions of 6.5% and self-consumption increases of 32.6%.

In parallel, peer-to-peer (P2P) and local energy trading mechanisms have attracted growing attention as means to improve renewable utilization, enhance local balancing, and reduce peak demand [5]. However, the performance of RECs is not determined only by technical coordination. Regulatory charges, tariff structures, and energy allocation rules can significantly affect the economic value of energy sharing and the distribution of benefits among participants [6]. This issue is particularly important in rural communities, where weaker grids, vulnerable consumers, and fairness considerations amplify the impact of tariff and settlement design [7], [8].

Recent literature recognizes RECs as relevant instruments for decentralized decarbonization, local value creation, and social engagement, spanning topics such as technical optimization, business models, governance, regulation, and social acceptance [7], [8]. Nevertheless, the field remains fragmented. Engineering-oriented studies often focus on operational optimization, while regulatory and economic analyses are frequently addressed separately. As a result, the interaction between market design, allocation rules, and network-constrained operation is still insufficiently captured in a unified framework.

A similar fragmentation is observed in the P2P energy trading literature. Existing works cover a broad range of approaches, including pricing mechanisms, auction models, game-theoretic formulations, blockchain-enabled settlement, and distributed optimization [5], [9]. Although these studies highlight the potential of P2P trading to improve DER integration and provide economic benefits to prosumers and consumers, practical deployment remains limited by regulatory complexity, settlement requirements, interoperability challenges, and fairness concerns. Furthermore, optimization-based methods proposed for community-scale operation often rely on simplified network models and neglect voltage or current constraints, which can be critical in weak rural feeders [10], [11], [12].

The allocation of locally generated energy is another key aspect in REC operation. Fixed sharing coefficients are simple to implement and administratively robust, but they may lead to inefficient outcomes under heterogeneous and time-varying demand and PV profiles. For this reason, dynamic sharing coefficients have received increasing attention, since they adapt energy allocation according to consumption patterns, temporal synchronism, or other contribution-based criteria [11]. Recent studies have proposed and compared several dynamic-sharing approaches, including proportional, correlation-based, trend-based, and hybrid methods, and have shown that allocation rules can materially affect how shared energy and economic benefits are distributed among members [6], [12].

Despite these advances, the literature on allocation and settlement remains only partially connected to grid-constrained operation and local market participation. Many studies assess allocation strategies through ex-post settlement or under simplified operating assumptions, while fewer works integrate dynamic sharing, hourly dispatch, demand response activation, and feeder constraints within a single optimization framework [13], [14]. This gap is particularly relevant for rural RECs, where operational limits and tariff structures may strongly influence both technical feasibility and economic performance.

Existing studies RECs often treat P2P trading, dynamic load balancing, pricing, storage operation or network constraints in isolation from one another. This article contributes by integrating these elements into a single MILP-based model and comparing how alternative load-sharing rules, under identical operating conditions, affect the technical and economic performance of a rural REC. Unlike studies that focus exclusively on billing or allocation, the proposed method considers both local exchange, battery operation, tariff-dependent costs, compensation for exports and the limits of the distribution network. The model is demonstrated using a rural REC in Portugal and should be transferable to other municipalities by adjusting the parameters for topology, demand, generation, storage and tariffs.

The innovative aspect of this work lies in the thorough assessment of P2P trading, alternative sharing coefficients, storage planning, tariff structures and network constraints, rather than in any single mechanism considered in isolation.

To address this gap, this paper proposes an optimization-based framework for rural RECs that compares a conventional retail configuration based on static/time-of-use (TOU) tariffs with an enhanced local market design combining P2P trading and dynamic energy sharing. The framework is parameterized by community topology, grid connection characteristics, DER assets, demand profiles, and local tariff structures, and is intended to be replicable across different case studies. The methodology is demonstrated using a Portuguese rural REC.

II. Methodology and Case Study

This work assesses the operational and economic benefits of coordinated energy management in. In particular, it evaluates how dynamic energy sharing, and P2P trading can improve system performance when explicitly accounting for wholesale market price signals and network constraints.

To this end, a set of progressively more sophisticated operational scenarios is analyzed, ranging from conventional retail-based operation to a fully coordinated REC framework. The comparison allows quantifying the incremental value of local energy markets and flexibility mechanisms beyond traditional tariff-based approaches.

A. REC Configuration

The proposed optimization framework is evaluated on a Portuguese REC, located in Sabugal, composed of four members: two consumers and two prosumers equipped with PV generation. One of the prosumers is additionally equipped with a battery energy storage system, enabling temporal shifting of locally generated energy.

Prosumers are allowed to generate surplus energy that may be locally consumed, exchanged within the REC, stored in the battery system, or exported to the upstream grid, while consumers rely on local resources or external supply to meet their demand. Distribution network constraints, including voltage magnitude limits and branch flow limits, are explicitly analyzed in all scenarios.

Figure 1 shows the characterization of the different members of the community, highlighting their role and the main information about them.

B. Market and Pricing Assumptions

The case study is developed considering the Portuguese electricity market and regulatory context. Wholesale electricity prices are represented by the Portuguese day-ahead market (OMIE) [15] price and are treated as exogenous and time-varying. These prices are used as a reference for wholesale-indexed mechanisms, namely for valuing surplus electricity exported by prosumers through commercialization arrangements such as aggregation.

At the retail level, REC members are modelled as low-voltage consumers supplied under retail electricity tariffs. Electricity imports from the grid are settled at the applicable retail tariff, which is represented under two pricing structures depending on the scenario: a flat tariff and a TOU tariff.

Energy exchanges within the REC, including energy sharing and P2P trading, are assumed to make use of the public distribution network. Consequently, the corresponding regulated network access charges applicable to shared energy are included in the settlement. Surplus electricity that is not consumed, stored, or traded locally is exported to the grid and remunerated at a wholesale-indexed export price linked to the day-ahead wholesale market.

When P2P trading is enabled, electricity exchanges among REC members are settled locally at an internal trading price constrained between the seller's export alternative (wholesale-indexed export price) and the buyer's retail alternative (retail import tariff). This pricing rule ensures that P2P transactions are economically beneficial for both parties relative to grid-based settlement.

C. Dynamic sharing

Within RECs, locally generated energy is allocated among members, playing a central role in determining both economic performance and grid-level impacts. In this work, the case study is designed to explicitly compare alternative dynamic energy sharing mechanisms applied to the same REC configuration, allowing the isolation and assessment of their effects on energy utilization, power flows, and interaction with the distribution network. Three energy sharing approaches are considered: net-consumption dynamic sharing, constant sharing coefficients, and hybrid dynamic sharing coefficients [16]. All sharing mechanisms are evaluated under identical network conditions, tariff assumptions and generation and demand profiles.

1) Energy Sharing Based on Net Consumption

Shared energy is allocated dynamically among REC members based on their net consumption at each time interval.

At every operational step, locally generated PV energy available for sharing is distributed proportionally to the instantaneous demand of each member, after accounting for self-consumption at the prosumer level.

This ensures that energy is preferentially assigned to members with higher contemporaneous demand, thereby maximizing local utilization of PV generation and reducing surplus exports to the upstream grid.

2) Energy Sharing Based on Constant Coefficients

The second approach adopts constant sharing coefficients, defined a priori and fixed over the entire simulation horizon. These coefficients represent predetermined shares of locally generated energy assigned to each REC member, independent of real-time consumption or generation conditions.

This mechanism reflects traditional collective self-consumption schemes commonly implemented in practice due to their simplicity and clarity. Constant coefficients offer stable and transparent allocation outcomes, which can be advantageous from a governance and settlement standpoint.

3) Energy Sharing Based on Hybrid Dynamic Coefficients

Hybrid dynamic sharing coefficients combine the stability of constant allocation with the responsiveness of net-consumption-based sharing. In this formulation, allocation coefficients are periodically updated or weighted using both predefined shares and real-time consumption signals.

Hybrid sharing mechanisms aim to balance efficiency and fairness by limiting excessive temporal volatility while still responding to operational conditions within the REC. By partially adapting to demand synchronism and PV availability, hybrid coefficients can improve local self-consumption and reduce grid stress without fully abandoning predictable allocation structures. In weak-grid rural contexts, this intermediate approach is particularly relevant, as it allows the REC to contribute to improved power flow patterns and voltage regulation while maintaining allocation transparency and replicability across communities.

D. Performance indicators

The performance of each scenario is evaluated using a set of economic and technical indicators relevant to energy communities and distribution networks. Economic performance is assessed through total electricity costs for REC members, including retail purchases, export revenues, P2P transaction outcomes, and network access charges associated with shared energy. Technical performance is evaluated by analyzing voltage profiles, branch loading, and compliance with distribution network operating limits. In addition, operational indicators such as renewable energy self-consumption, volume of P2P energy exchanges, and battery utilization are considered. The comparative analysis of these indicators provides insights into the benefits of coordinated REC operation relative to conventional retail-based arrangements in weak distribution networks.

E. Case Studies description

Four scenarios are considered to evaluate the impact of increasing levels of coordination and market integration for P2P trading in RECs.

1) Fixed retail-based operation (S0)

REC members operate independently under a flat retail tariff. Electricity demand is supplied by the retailer, while surplus PV generation is exported to the grid at a wholesale-indexed price. No local trading, energy sharing, battery optimization, or demand response is enabled.

2) Time of use tariffs-based operation (S1)

REC members are subject to a TOU retail tariff. No coordination or local energy trading is allowed, isolating the effect of retail price variability.

3) Peer to Peer energy trading operation (S2)

P2P energy trading is enabled among REC members. Prosumers sell surplus electricity directly to consumers within the community at a locally cleared price bounded by retail import tariffs and wholesale-indexed export remuneration. Remaining imbalances are settled with the grid.

4) Coordinated rec operation (S3)

Dynamic energy sharing, P2P trading, and battery operation are jointly optimized while accounting for distribution network constraints and time-varying price signals. Figure 2 shows the proposed methodology for the optimization framework described in the next section. The methodology is divided into three main tasks, the input data used in the optimization model, the settlement and allocation, and the performance analysis indicators.

III. Optimization model

To ensure a consistent and unbiased comparison among the three sharing approaches, all cases are evaluated using the same mixed-integer linear programming (MILP) framework. The optimization is solved over the same horizon and inputs (load profiles, PV generation, storage parameters, retail tariffs, export remuneration, and network constraints), while the only element that changes across scenarios is the energy-sharing rule used to compute the allocation of locally available energy among REC members. The MILP jointly determines, at each time interval, the operating decisions associated with: (i) energy exchanges within the REC (including P2P transfers), (ii) imports from and exports to the main grid, and (iii) battery charging/discharging.

A. Sets and parameters

In the optimization model, the following sets and parameters were considered:

- $M = \{1, \dots, i\}$, set of members of the REC, with $i = 4$; $C \subset N$, sub-set of consumers, indexed by c; and $P \subset N$, sub-set of prosumers, indexed by p;
- $T = \{1, \dots, nT\}$, set of 15 minutes intervals in a day, with $nT = 96$;
- $L_{i,t}$, energy demand, in *kWh*, of member *i* at time interval *t*;
- $PV_{i,t}$, PV generation, in *kWh*, of prosumer *p* at time interval *t*;
- c_t^{imp}, energy import tariff, in *€/kWh*, at time interval *t*;
- c_t^{exp}, energy export tariff, in *€/kWh*, at time interval *t*;
- $c_t^{buy,P2P}$, P2P buying price, in *€/kWh*, at time interval *t*;
- $c_t^{sell,P2P}$, P2P selling price, in *€/kWh*, at time interval *t*;
- c^{RESP}, utilization of public grid cost, in *€/kWh*;
- $\alpha_{i,t}$, dynamic sharing coefficient of member *i* at time interval *t*;

- α_i, constant sharing coefficient of member *i;*
- $\lambda \in [0,1]$, weighting factor used in the hybrid sharing rule;

B. Decision variables

The decision variables considered for the formulation of the problem are presented below:

- $E_{i,t}^{imp}$, energy imported from the grid, in *kWh*, of member *i* at time interval *t*;
- $E_{i,t}^{exp}$, energy exported to the grid, in *kWh*, from prosumer *p* at time interval *t*;
- $E_{p,t}^{PV}$, PV generation, in *kWh*, locally used by prosumer *p* at time interval *t*;
- E_{t}^{REC}, total shared energy, in *kWh*, within the REC at time interval *t*;
- $E_{t}^{ch,bat}$, energy injected into the battery, in *kWh,* at time interval *t*;
- $E_{t}^{dis,bat}$, energy discharged from the battery, in *kWh,* at time interval *t*;

C. Constraints

The proposed MILP model is subject to a set of operational constraints that ensure the physical consistency of energy exchanges within the REC and the feasible operation of the battery energy storage system. The proposed MILP model is subject to a set of operational constraints that ensure the physical consistency of energy exchanges within the REC and the feasible operation of the battery energy storage system. These constraints can be grouped into four main categories: i) energy sharing allocation, ii) shared energy balance, iii) member energy balance, and iv) battery operation constraints. Since the main contribution of this work lies in the energy sharing mechanisms, only the constraints associated are explained.

Let E_t^{REC} denote the total shared energy within the REC at time interval *t*, and let $E_{i,t}^{RECv}$ denote the portion received by member interval *i*. The allocation is governed by sharing coefficients that determine the fraction of E_t^{REC} assigned to each member.

1) Energy sharing based on net consumption

The net-consumption-based rule allocates shared energy proportionally to each member's net demand. For prosumers, the net demand is the positive difference between load and local PV generation; for consumers it equals the load:

$$ND_{i,t} = max(L_{i,t} - PV_{i,t}, 0), i \in P, t \in T \quad (1)$$

$$ND_t^{tot} = \sum_{i \in M} N D_{i,t}, t \in T \quad (2)$$

$$\alpha_{i,t} = \frac{ND_{i,t}}{ND_t^{tot}}, i \in M, t \in T, ND_t^{tot} > 0 \quad (3)$$

$$\alpha_{i,t} = 0, i \in M, t \in T, ND_t^{tot} = 0 \quad (4)$$

$$E_{i,t}^{RECv} = \alpha_{i,t} E_t^{REC}, i \in M, t \in T \quad (5)$$

2) Energy sharing based on constant coefficients

In the constant-coefficient rule, each member receives a fixed share of E_t^{REC} over the entire horizon, computed from its fraction of total REC demand:

$$\alpha_i = \frac{\sum_{t \in T} L_{i,t}}{\sum_{t \in T} \sum_{j \in M} L_{j,t}}, i, j \in M, t \in T \quad (6)$$

$$E_{i,t}^{RECv} = \alpha_i E_t^{REC}, i \in M, t \in T \quad (7)$$

3) Energy sharing based on hybrid coefficients

The hybrid rule combines the constant and dynamic coefficients through a weighting factor $\lambda \in [0,1]$:

$$\alpha_{i,t}^{hyb} = \lambda \alpha_i + (1 - \lambda) \alpha_{i,t}, i, j \in M, t \in T \quad (8)$$

$$E_{i,t}^{RECv} = \alpha_{i,t}^{hyb} E_t^{REC}, i \in M, t \in T \quad (9)$$

The complete MILP additionally includes shared-energy conservation constraints linking sent and received energy, member energy balances ensuring demand satisfaction via grid, PV, sharing, and storage, PV availability limits, and battery operational constraints (charging/discharging bounds, state-of-charge dynamics, and non-simultaneous operation enforced via a binary variable).

D. Objective funtion

The objective function maximizes the total profit of the renewable energy community over the scheduling horizon by balancing the economic benefits of local coordination against the associated operating costs.

$$max\ REC_{PROFIT} = R^{exp} + R^{buy,P2P} - C^{sell,P2P} - C^{imp} - C^{RESP} \quad (10)$$

$$R^{exp} = \sum_{t \in T} \sum_{p \in P} c_t^{exp} E_{i,t}^{exp}, p \in P, t \in T \quad (11)$$

$$C^{buy,P2P} = \sum_{t \in T} c_t^{buy,P2P} E_t^{REC}, t \in T \quad (12)$$

$$C^{sell,P2P} = \sum_{t \in T} c_t^{sell,P2P} E_t^{REC}, t \in T \quad (13)$$

$$C^{imp} = \sum_{t \in T} \sum_{i \in M} c_t^{imp} E_{i,t}^{imp}, i \in M, t \in T \quad (14)$$

$$C^{RESP} = \sum_{t \in T} c^{RESP} E_t^{REC}, t \in T \quad (15)$$

IV. Results and Discussion

This section analyzes the performance of the proposed REC under the case studies defined in Section II. The objective is to evaluate the impact of the different operational scenarios on the REC from technical and economic perspectives, considering grid energy exchanges, local peer-to-peer transactions, battery utilization, and overall profitability.

The model is validated using a framework consisting of stepwise scenarios. S0 defines the conventional baseline for retail trade, S1 isolates the effect of time-of-use tariffs, S2 isolates the value of P2P trading, and S3 evaluates coordinated operation with alternative allocation rules. As all scenarios use the same data on demand, solar panels, tariffs, storage and the grid, the observed differences can be attributed to the coordination mechanism under investigation.

Table I compares the operational and economic performance of the proposed REC under the analyzed scenarios. As expected, S0 represents the most conventional operating mode, with no internal trading or coordinated sharing. This scenario yielded the highest REC profit (€49.92), mainly due to the high export revenue obtained from surplus PV injection to the grid. However, it also exhibited the highest grid import (9969.89 kWh), indicating a strong dependence on external grid exchanges and limited local utilization of renewable generation.

In scenario S1, with TOU tariffs, the REC becomes slightly more efficient, as grid imports and exports decrease to 9487.03 kWh and 3436.53 kWh, respectively. Nevertheless, the total import cost increases and the REC profit drop significantly to €33.24. This indicates that, under the adopted tariff structure, the time-varying retail price signal alone is not sufficient to improve the overall economic performance, despite the slightly more active use of storage.

TABLE I. COMPARISON OF ENERGY TRADING IN THE DIFFERENT SCENARIOS.

Scenario		**Grid import (kWh)**	**Grid export (kWh)**	**P2P sharing (kWh)**	**Import cost (€)**	**Export revenue (€)**	**P2P buy revenue (€)**	**P2P sell cost (€)**	**RESP cost (€)**	**REC profit (€)**	**Battery SOC (kWh)**
S0		9969.89	3689.72	0.00	104.93	154.85	—	—	—	49.92	1199.52
S1		9487.03	3436.53	0.00	115.39	148.63	—	—	—	33.24	1239.93
S2		9037.67	3122.20	449.79	108.67	147.67	4.48	2.77	4.49	36.22	1161.28
S3	Net consumption	9037.22	3121.94	450.04	108.66	147.68	4.48	2.78	4.50	36.22	1161.22
	Constant coefficients	9255.51	3271.79	276.57	111.93	148.23	2.75	1.64	2.77	34.64	1195.12
	Hybrid coefficients	9177.60	3215.53	336.54	110.77	148.04	3.35	2.06	3.37	35.20	1182.53

The P2P trading (scenario S2) substantially improves local coordination. Compared with S1, grid imports fell to 9037.67 kWh and exports to 3122.20 kWh, while 449.79 kWh are transacted locally within the REC. These results confirm that internal trading contributes to better local matching between demand and generation, reducing the interaction with the upstream grid. This scenario demonstrates that enabling internal transactions can recover part of the economic loss observed in S1 while improving local energy use.

In scenario S3, the different sharing mechanisms lead to distinct outcomes. The net-consumption-based sharing approach achieves the best technical performance, with the lowest grid import (9037.22 kWh), the lowest grid export (3121.94 kWh), and the highest shared energy volume (450.04 kWh). This confirms that dynamic coefficients based on real-time net demand provide the most effective allocation of local surplus, maximizing the local absorption of renewable generation. However, the corresponding REC profit (€34.58) remains almost identical to that of S2, suggesting that the economic advantage of this technically superior strategy is limited by the current internal price structure and sharing-related charges.

In contrast, the constant-coefficient sharing approach yields the weakest local performance among the sharing-based scenarios. Grid imports and exports rise to 9255.51 kWh and 3271.79 kWh, respectively, while P2P sharing decreases markedly to 276.57 kWh. This indicates that fixed coefficients are less capable of adapting to the temporal variability of load and PV generation, leading to a less efficient use of locally available energy.

The hybrid approach provides an intermediate solution between dynamic and constant approaches. It achieves 336.54 kWh of shared energy, with grid import and export values lower than those obtained under constant coefficients but higher than those achieved with net-consumption sharing. This scenario has the highest profit among the coordinated scenarios (€35.20), suggesting that it offers the best compromise between local technical efficiency and economic performance. This result is particularly relevant as it indicates that combining fixed and dynamic coefficients can improve the balance between fairness, operational flexibility, and profitability.

Overall, the results show that dynamic net-consumption sharing maximizes local energy exchange and minimizes grid dependency, while the hybrid method yields the best economic compromise under the adopted pricing assumptions. By contrast, constant coefficients are less effective, and TOU pricing alone is insufficient to unlock the full value of REC coordination. Figure 3 shows the results of the optimization model for Scenario S3, considering the different energy sharing strategies. In the figures it is described the energy flow within the REC.

V. CONCLUSIONS

This paper proposed a MILP-based framework to assess rural RECs under increasing levels of coordination, comparing conventional retail operation with TOU tariffs, P2P trading, and alternative energy-sharing rules. Results from the Portuguese case study show that TOU pricing alone reduced grid imports and exports by 4.8% and 6.9%, respectively, but decreased REC profit by 33.4%, indicating that tariff variation alone is insufficient to improve economic performance. Enabling P2P trading reduced imports by a further 4.7% and exports by 9.1% relative to TOU operation, while increasing profit by 9.0%, confirming better local matching between demand and PV generation. Among the coordinated strategies, net-consumption sharing achieved the best technical performance, with 2.4% lower imports, 4.6% lower exports, and 62.7% more shared energy than constant coefficients. Overall, dynamic sharing improves local energy use, while hybrid sharing offers the best technical-economic compromise under current tariff assumptions.

The results are specific to the analyzed four-member Portuguese rural REC and depend on the adopted tariff structure, export remuneration, P2P price bounds, and network access charges. Therefore, future work will extend the validation to larger communities, alternative feeder topologies, stochastic demand/PV profiles, and different regulatory settings. Nevertheless, the framework is transferable by adapting the input data and constraints to other REC configurations.

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ANNEX

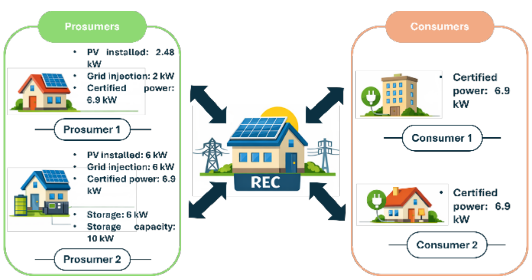

Figure 1. Sabugal's REC members.

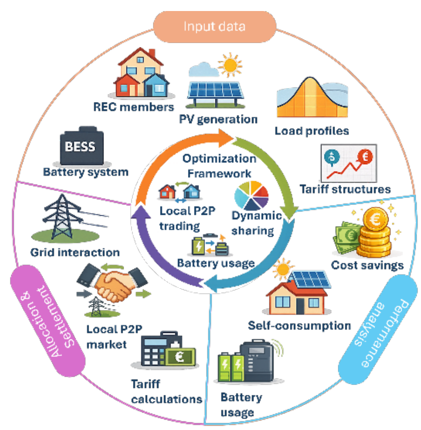

Figure 2. Proposed methodology for the optimization framework.

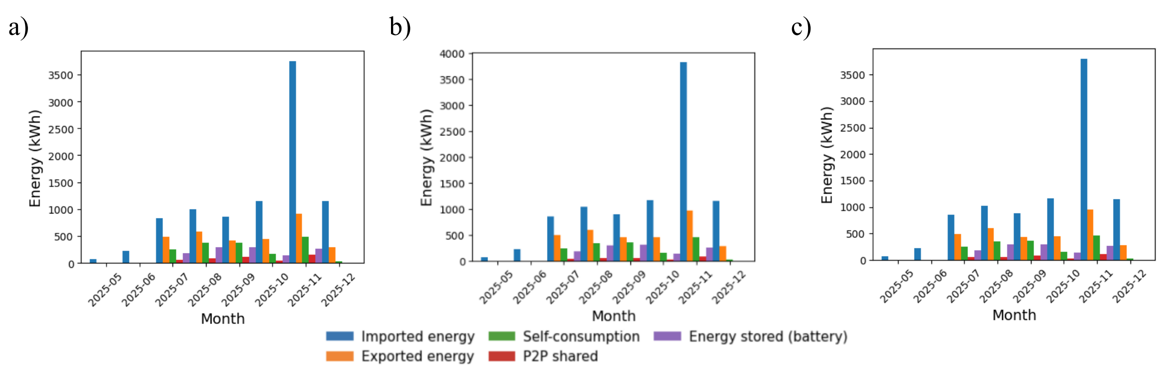

Figure 3. REC's montly energy balance in Scenario S3, based on: a) net consumption; b) on constant coefficients; c) hybrid coefficients.