Strategies for Fair Distribution of Collective Benefits in Renewable Energy Communities

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***Abstract*—The rapid rise of Renewable Energy Communities (REC) offers unique opportunities for decentralizing and decarbonizing energy systems but also brings challenges in designing fair mechanisms for distributing the benefits of collective self-consumption. This paper evaluates three approaches for benefit-sharing based on the Shapley value, direct marginal contributions, and system marginal cost. A case study compares these methodologies in terms of practicality, fairness, and impact on financial returns. Additionally, this paper proves that settling local transactions using system marginal costs ensures that all REC participants incur equal or lower costs compared to operating independently.**

***Index Terms*--Renewable Energy Communities, Marginal Contribution, Benefit Distribution, Cooperative Game Theory, Energy Investment.**

I. INTRODUCTION

Renewable Energy Communities (RECs) play a key role in promoting local energy self-consumption and sustainability [1], [2], but fair benefit allocation among members remains a challenge [3], [4]. This paper presents and compares three methods for allocating benefits in RECs: the Shapley Value for Incremental Value (SV-IV), the Direct Marginal Contribution for Incremental Value (DMC-IV), and the System Marginal Cost (SMC). While the Shapley value approach offers a cooperative game-theoretic benchmark, its complexity limits practical application [5]. The direct marginal contribution approach provides a simpler alternative, and system marginal cost aligns with market-based principles. A case study evaluates these methods regarding fairness, computational efficiency, and their ability to engage REC members. The framework is designed for scalability and adaptability across different REC contexts, supporting decision-making in benefit allocation.

II. METHODOLOGY

To assess the contributions of the REC members to the REC collective benefit, we use three indicators:

- The Shapley Value for Incremental Value (SV-IV), which assesses value increments by averaging contributions across all possible coalitions [6], [7].
- The Direct Marginal Contribution for Incremental Value (DMC-IV), which evaluates the value increment when a member is added to the full coalition [8], [9].
- The System Marginal Cost, which allows to compute individual financial savings by comparing each member's financial costs within the REC to their costs in isolation, using the system marginal cost as the internal exchange price [10]. The mathematical proof that, in all cases, using marginal costs as internal exchange price results in a lower or equal cost for all participants is also presented.

The analysis is divided into two stages: first, a simulation-based study using a controlled REC scenario, and second, an application to real-world data from a REC comprising 9 members.

A. Determination of the minimum REC cost

The optimization model, similar to the one presented in [10], in essence minimizes the operation costs of the REC. Equations (1)-(3) represent a normalized and simplified version of the problem without batteries. Members may either buy from their retailer, sell to their aggregator, or consume the excess generation from other REC members by paying the self-consumption grid tariff. Note that, as this is an overall cost-minimization problem, settlement of each member's local sales and purchases within the REC do not appear in (1), and are subject to the different methodologies presented in the following sections of this paper:

$$min\sum_{t\in T}\left(\sum_{n\in N}\left(E_{n,t}^{SUP}\cdot\hat{\lambda}_{n,t}^{buy}-E_{n,t}^{SUR}\cdot\hat{\lambda}_{n,t}^{sell}+E_{n,t}^{PUR}\cdot\hat{\lambda}_{t}^{grid}\right)\right) \quad (1)$$

Subject to:

$$\sum_{n}\left(E_{n,t}^{SALE}\right)-\sum_{n}\left(E_{n,t}^{PUR}\right)=0:\lambda_{t}^{BAL} \quad (2)$$

$$E_{n,t}^{SUP} - E_{n,t}^{SUR} + E_{n,t}^{PUR} - E_{n,t}^{SALE} = \hat{E}_{n,t}^{C} - \hat{E}_{n,t}^{G} : \lambda_{n,t}^{nBAL} \quad (3)$$

Where:

n: REC member index.

t: time index (i.e., hour of day)

$\hat{E}_{n,t}^{C}$: Energy consumption of member n during time t.

$\hat{E}_{n,t}^{G}$: Energy generation of member n during time t.

$\hat{\lambda}_{n,t}^{buy}$: Energy buying price from retailer for n during t.

$\hat{\lambda}_{n,t}^{sell}$: Energy selling price to aggregator for n during t.

$\hat{\lambda}_{t}^{grid}$: Self-consumption grid access tariff during t.

$E_{n,t}^{SUP}$: Energy bought from retailer by member n during t.

$E_{n,t}^{SUR}$: Energy surplus sold to the aggregator by n during t.

$E_{n,t}^{PUR}$: Energy purchased from REC by n during t.

$E_{n,t}^{SALE}$: Energy sold by n in the REC in a pool-like approach.

$E_{n,t}^{CMET}$: Net consumption in meter n during t.

λ_{t}^{BAL}: SMC as the shadow price of the energy balance (2).

$\lambda_{n,t}^{nBAL}$: Dual variable for meter energy balance (3).

B. Indicators for Member Contribution Evaluation

The optimization model defines the total REC operational cost, which serves as the basis for evaluating member contributions. The following indicators quantify each member's impact on collective cost savings, each employing a distinct approach to benefit allocation.

1) Shapley Value for Incremental Value

The Shapley value, derived from cooperative game theory, is a robust methodology for fairly distributing costs or benefits among members of a coalition based on their marginal contributions [11]. For a community N with n members, the Shapley value for a member i is defined as:

$$\phi_i = \sum_{S \subseteq N \setminus \{i\}} w \,.\, [v(S \cup \{i\}) - v(S)] \quad (4)$$

where:

- N: Set of all REC members.
- S: any coalition not including member i.
- $v(S)$: Value of coalition S, representing the total benefits or cost savings achieved by S.
- $v(S \cup \{i\}) - v(S)$: Marginal contribution of member i when joining coalition S.
- $w = \frac{|S|!\,.(n-|S|-1)!}{n!}$: weight based on the probability of i being added to a coalition S.

In this study, we assess cooperative value increments, where the value function, $v^*(S)$, reflects cost savings from cooperation compared to the individual behaviors:

$$v^*(S) = \sum_{j \in S} c(\{j\}) - c(S) \quad (5)$$

The Shapley Value for Incremental Value (SV-IV) is:

$$\phi_i^{IV} = \sum_{S \subseteq N \setminus \{i\}} w \,.\, [v^*(S \cup \{i\}) - v^*(S)] \quad (6)$$

where the marginal contribution $v^*(S \cup \{i\}) - v^*(S)$ reflects the difference between the cooperative cost savings achieved through cooperation with and without the member. The collective benefits correspond to the total cost savings achieved by the REC through energy sharing and optimization. The SV-IV quantifies each member's contribution to these savings, serving as a basis for benefit allocation, so that members with higher contributions to reducing the overall cost receive a greater share of these benefits. However, this method is computationally intensive for larger communities and can be difficult to explain and interpret.

2) Direct Marginal Contribution for Incremental Value

The Direct Marginal Contribution for Incremental Value (DMC-IV) provides a simplified measure of individual impact [9]. For a member i, it is calculated as:

$$DMC_i^{IV} = v^*(S) - v^*(N \setminus \{i\}) \quad (7)$$

where $v^*(S)$ refers to the REC's cost savings with all members, and $v^*(N \setminus \{i\})$ refers to its value excluding i.

The DMC-IV measures the impact of each member's participation on the total REC cost by comparing the collective cost with and without that member. Members with higher DMC-IV values are assigned a larger share of the savings, as they have a more significant impact on the REC cost reduction. While computationally efficient, this approach does not account for all interactions between members, offering a less comprehensive view compared to the SV-IV.

3) System Marginal Cost Impact

The System Marginal Cost (SMC) is the shadow price λ_t^{BAL} that results from the optimization model and can be used as the price to settle the local energy exchanges within the REC [12], [13], providing a direct way to share the collective REC benefits. The savings for each member are determined by comparing these financial costs with the hypothetical scenario where members operate independently, relying solely on external market transactions.

We prove now that using the SMC as the local transactions price guarantees that no member incurs in losses compared to its induvial behavior. For this, we deduce the dual problem by applying duality theory, which in its normalized form, is given by (8)-(12):

$$max \sum_t \left(\sum_n \left(\lambda_{n,t}^{nBAL} \cdot \left(\hat{E}_{n,t}^{C} - \hat{E}_{n,t}^{G} \right) \right) \right) \quad (8)$$

Subject to:

$$\lambda_{n,t}^{nBAL} \leq \hat{\lambda}_{n,t}^{buy} : E_{n,t}^{SUP} \quad (9)$$

$$-\lambda_{n,t}^{nBAL} \leq -\hat{\lambda}_{n,t}^{sell} : E_{n,t}^{SUR} \quad (10)$$

$$-\lambda_{t}^{BAL} + \lambda_{n,t}^{nBAL} \leq \hat{\lambda}_{t}^{grid} : E_{n,t}^{PUR} \quad (11)$$

$$\lambda_t^{BAL} - \lambda_{n,t}^{nBAL} \leq 0: E_{n,t}^{SALE} \tag{12}$$

From the dual problem we can draw several conclusions. First, from constraints (9) & (10) we deduce (13):

$$\hat{\lambda}_{n,t}^{sell} \leq \lambda_{n,t}^{nBAL} \leq \hat{\lambda}_{n,t}^{buy} \tag{13}$$

which means that the local marginal cost of energy at any meter and at any time ($\lambda_{n,t}^{nBAL}$) is between the selling price to the aggregator and buying price from the retailer. Note also that having any selling price higher than its respective buying price will make the problem dual-infeasible (or primal-unbounded).

Similarly, we can rewrite (11) and (12) as (14) and (15) respectively:

$$\lambda_{n,t}^{nBAL} \leq \lambda_t^{BAL} + \hat{\lambda}_t^{grid}: E_{n,t}^{PUR} \tag{14}$$

$$\lambda_t^{BAL} \leq \lambda_{n,t}^{nBAL}: E_{n,t}^{SALE} \tag{15}$$

In addition, complementary slackness optimality conditions require that, when a meter is purchasing locally (i.e., $E_{n,t}^{PUR} > 0$), constraint (14) must hold as equality, and likewise for selling locally and constraint (15). This allows to substitute $\lambda_{n,t}^{nBAL}$ in (13) to deduce (16) and (17):

$$\hat{\lambda}_{n,t}^{sell} \leq \lambda_t^{BAL} + \hat{\lambda}_t^{grid} \leq \hat{\lambda}_{n,t}^{buy} \; if \; E_{n,t}^{PUR} > 0 \tag{16}$$

$$\hat{\lambda}_{n,t}^{sell} \leq \lambda_t^{BAL} \leq \hat{\lambda}_{n,t}^{buy} \; if \; E_{n,t}^{SALE} > 0 \tag{17}$$

Inequality (16) proves that any meter purchasing locally, if the purchase is settled at a price equal to the SMC (λ_t^{BAL}), will pay a lower or equal price than purchasing it from its retailer, while (17) proves that selling locally will be done at a higher or equal price than selling to its aggregator. Therefore, both cases result in higher welfare for all REC participants. This proof can be generalized for more complex versions of the model (e.g., adding batteries or generators with positive variable cost), but that generalization remains for future works.

Together, these three approaches provide different perspectives on benefit allocation within the REC. The SV-IV and DMC-IV methods evaluate the cooperative value generated by each member, attributing larger shares of collective savings to those with higher contributions. In contrast, the SMC approach directly determines financial savings by comparing each member's costs inside and outside the REC, ensuring that no participant incurs higher costs than they would in isolation. These methods form a framework that balances cooperative contributions and financial impact, ensuring fair and efficient REC management.

III. CASE EXAMPLES

The results from the three methods are compared in a case study to provide a practical perspective alongside theoretical fairness metrics, using both simulated and real-world REC scenarios. The simulation tests the indicators under controlled conditions with representative member profiles [14]. The real-world case applies the methods to a REC of nine prosumers, with real consumption and generation data. Results are assessed based on fairness, computational complexity, and practical applicability, ensuring a comprehensive evaluation that balances theoretical rigor and real-world relevance.

The controlled scenario models a REC with five distinct member profiles, each designed to assess the robustness and applicability of the SV-IV, DMC-IV, and SMC methodologies under specific conditions.

All computations were implemented in Python, using PuLP library [15] with CPLEX solver.

A. Control Scenario and Expected Outcomes

The simulated REC includes the following member profiles:

- Member with Maximum Benefit (*max_ben*): member with a highly consumption and generation profile, maximizing individual self-consumption and minimizing reliance on external energy sources. Expected to exhibit the highest contribution across all indicators due to optimal self-consumption.
- Neutral Member (*control*): member with similar consumption and generation, resulting in a neutral contribution to the REC. Designed to show zero contribution, as it neither benefits nor harms the REC.
- Unfavorable Member (*unfav*): consumes exclusively during night-time hours, without any energy generation. The purpose is to simulate a member with a potentially negative impact, though contributions remain non-negative due to the incremental value perspective.
- Regular Member 1 (*reg1*): Household with children, where consumption increases during late afternoon and evening hours, reflecting typical domestic activity patterns. Expected to exhibit moderate contributions.
- Regular Member 2 (*reg2*): Single professional with steady daytime activity and moderate evening consumption, aligning with typical work-from-home behaviors. Expected to exhibit moderate contributions.

Each profile was designed based on typical Portuguese residential consumption patterns for late September, with 12 hours of sunlight per day. The member profiles were modeled as hourly time series over a 24-hour period, incorporating realistic market energy prices for purchase, sale, and grid usage. These prices, uniform across all members, were derived from real market data corresponding to a representative day in late September. The proposed indicators were computed for each member to assess their contribution to the collective REC benefits.

B. Real Scenario

For this scenario, data are taken from a real-world REC in operation, Caxias Living Lab [16], located in Lisbon, Portugal. The dataset represents energy generation and consumption patterns for nine members of this REC, all of them with PV generation. Except for one member, all have also battery storage configured with similar settings [17].

The nine members analyzed in this study represent diverse consumption and generation profiles:

- Members '0' through '5': Residential users with distinct consumption and generation behaviors. Member '1' is the only residential user without battery storage.
- Member '6': A community center with high energy use.
- Member '7': A school with daytime energy demand.

- Member '8': A municipal market with significant consumption and generation capacity.

The analysis spans three representative months in 2023 — July (summer), October (autumn), and December (winter) — to capture seasonal variations. The focus is on the second week of each month to ensure representative energy profiles while avoiding holiday periods or atypical consumption patterns.

IV. RESULTS

This section presents the results for the control case and the application to real-world data. All values are expressed in euros, facilitating a practical interpretation of the results.

A. Control Scenario Analysis

The control case provides a benchmark for evaluating the behavior of the proposed methods. Table I summarizes the results for the SV-IV, DMC-IV, and SMC approaches.

TABLE I SV-IV, DMC-IV AND SMC RESULTS - CONTROL CASE

Cost Savings	**Member**				
	max_ben	***control***	***unfav***	***reg1***	***reg2***
SV-IV	0.0528	0.0000	0.0000	0.0294	0.0164
DMC-IV	0.0986	0.0000	0.0000	0.0519	0.0260
SMC	0.11	0.02	0.00	0.04	0.02

Member *max_ben* exhibits the highest contribution across all indicators, with cost savings of 0.0528, 0.0986, and 0.11 from SV-IV, DMC-IV and SMC method respectively. confirming its key role in the community. Members *control* and *unfav* have negligible contributions also with all methods, indicating that their inclusion does not add value to the REC. However, while *unfav* remains neutral across all metrics, showing no significant impact or benefit, *control* still achieves slight savings under the SMC approach, likely due to favorable transactional conditions. Meanwhile, members *reg1* and *reg2* show moderate contributions in all metrics, reflecting a balanced impact. Overall, the results confirm that members contributing more to the community tend to benefit financially, validating a similar consistency among the metrics.

B. Real-World Scenario Analysis

This section presents the results of the real-world case study, evaluating the impact of each method on benefit allocation and financial outcomes. The results are presented separately for each indicator to highlight their individual contributions.

4) Shapley Value (SV-IV)

Figure 1 illustrates the SV-IV results across different seasons. In July, Member 6 stands out as the dominant contributor, showing a decreasing trend throughout the week, while Members 0, 5, and 8 also exhibit significant contributions. In October, Member 6 maintains the highest contributions but follows a downward trend. Most other members exhibit relatively stable and lower contributions. This pattern can be explained by seasonal variations in energy generation and consumption among REC members. Members 6 emerge as the dominant contributor in July and October, aligning with its higher energy generation and self-consumption capabilities. In December, contributions are generally stable across all members reflecting the seasonal decline in generation, except for a single peak day where Members 8 and 6 exhibit a sharp increase, likely due to a temporary rise in their energy generation.

These results suggest that in summer and autumn, certain members play a more dominant role in value generation, while winter exhibits a more uniform contribution pattern, with isolated spikes driven by specific conditions. The members with lower contributions tend to remain stable, with greater dispersion in July and minimal variations in December.

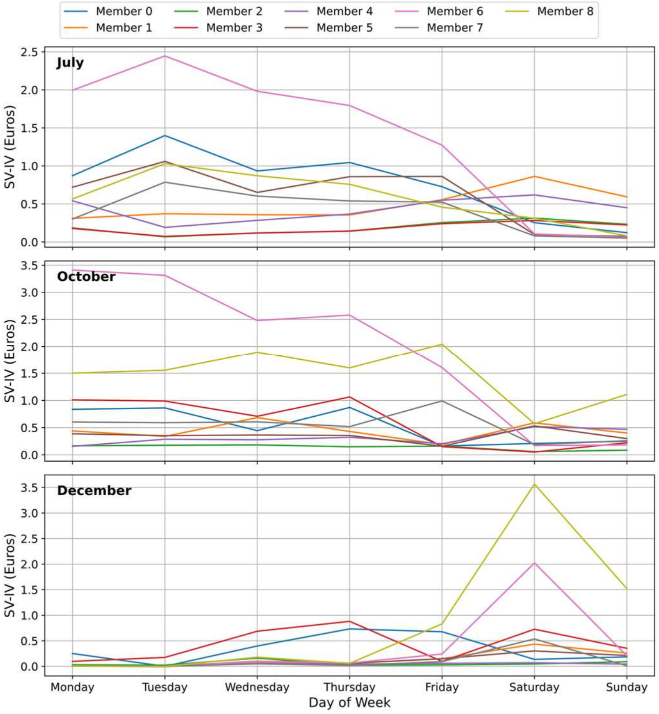

Figure 1. SV-IV for all members during 2^{nd} week of July (10th-16th), October (9th-15th) and December (11th-17th).

5) Direct Marginal Contribution (DMC-IV)

Figure 2 shows DMC-IV results across seasons, showing rankings that closely align with the SV-IV approach but with consistently higher values. This difference is expected, as DMC-IV captures direct marginal contributions without considering synergies between members, unlike the SV-IV, which distributes contributions among all coalition possibilities.

In July and October, Member 6 maintains the highest contributions, followed by Members 0, 5, and 8, mirroring the SV-IV results. However, contributions exhibit greater variability, particularly for Member 6, whose values decrease more sharply over time. As explained before, this fluctuation may be due to the fact that DMC-IV is a direct marginal measure, making it more sensitive to daily variations in energy transactions. In December, contributions remain relatively uniform across members, reflecting the seasonal reduction in energy generation, except for a notable peak for Members 8 and 6 on a single day, consistent with the SV-IV pattern.

Overall, DMC-IV and SV-IV provide similar insights into member impact, with similarity in rankings suggesting a strong correlation between them and reinforcing their consistency. Additionally, higher values and sharper individual fluctuations in DMC-IV highlight the direct marginal effect of each member on the REC, confirming its role as a computationally simpler yet effective alternative to SV-IV.

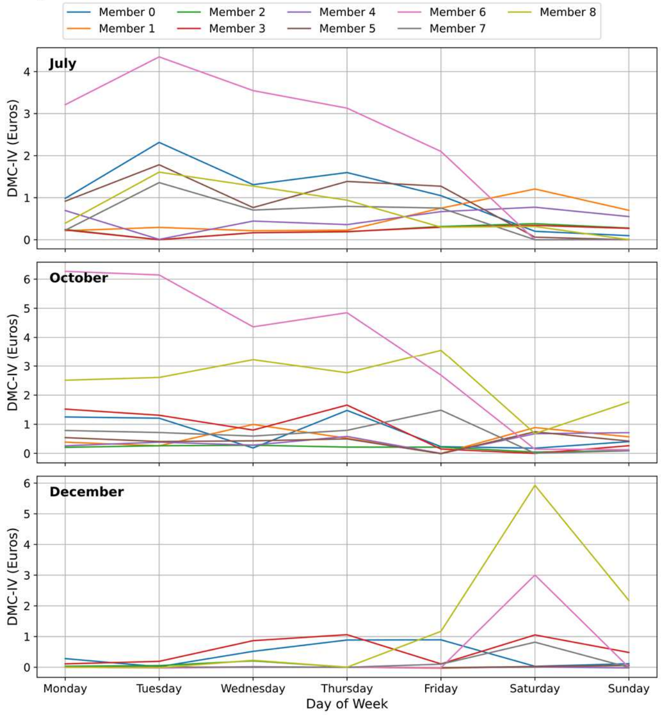

Figure 2. DMC-IV for all members during 2nd week of July (10th-16th), October (9th-15th) and December (11th-17th).

6) *System Marginal Cost (SMC)*

Figure 3 illustrates the SMC approach results, showing the savings per member using this approach (bottom) and their corresponding average SV-IV contributions over the same periods (top). Figure 3 reveals that savings vary significantly among members, with higher savings observed in July and October, while December shows generally lower values. This seasonal pattern aligns with the variations in energy generation and self-consumption potential, which directly influence each member's ability to minimize external market transactions.

Figure 3 (top) presents the distribution of SV-IV contributions, with some members consistently achieving higher contributions. The comparison between these figures indicates higher cooperative contributions generally lead to greater financial savings, though with some variations in magnitude. This suggests that while cooperative impact plays a significant role in financial benefits, additional factors - such as market price fluctuations - also shape the final cost reductions.

In July, Members 0, 5, 6, and 8 achieve the highest savings, aligning with their strong SV-IV contributions. This correlation highlights that in periods of high solar generation, members who contribute more to collective benefits tend to maximize their financial returns by reducing external purchases. In October, Member 6 remains the highest contributor in both metrics, while Member 8 also maintains a significant role, indicating that these members benefit from both high generation and favorable self-consumption conditions. In December, Members 3 and 8 achieve the highest savings, despite Member 6 maintaining a notable SV-IV contribution. This discrepancy may stem from lower solar availability and shifts in energy usage patterns, which alter the balance between cooperation and direct financial impact.

Overall, this comparison reinforces that greater cooperative contributions tend to result in higher financial benefits, although individual energy behaviors and market conditions introduce some variations.

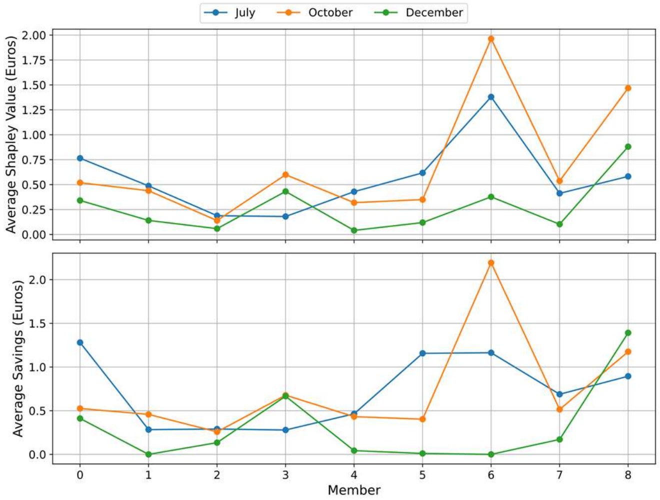

Figure 3. Average SV-IV (top) and Average Savings (bottom) across 2nd week of July (10th-16th), October (9th-15th) and December (11th-17th).

V. CONCLUSION

This study evaluated three methods for allocating REC benefits: the Shapley Value (SV-IV), Direct Marginal Contribution (DMC-IV), and the System Marginal Cost (SMC) approach. The results demonstrate strong consistency between all three methods, as they generally produce similar member rankings, reinforcing the robustness of these indicators for assessing benefit allocation within an REC.

DMC-IV aligns closely with SV-IV but is more transparent and computationally efficient, making it preferable for large RECs. SMC, based on financial savings, also reflects cooperative contributions, but its applicability extends beyond fairness considerations, as it directly influences financial impact of energy transactions within the REC.

While all methods provide coherent insights and similar rankings, their suitability depends on the specific objectives of the REC, whether prioritizing fairness, computational efficiency, or direct financial impact. Seasonal variations significantly impact member benefits, reinforcing the need for temporal granularity in benefit allocation. Members with higher cooperative impact tend to achieve greater financial benefits, but this correlation varies across time periods.

Future work should explore scalability to larger RECs, predictive models for evaluating new members, and the role of community-scale storage in benefit allocation. By balancing fairness, simplicity, and efficiency, this study provides a structured approach to REC management, supporting equitable and informed decision-making.

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