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Analysing Energy Allocation in Renewable Energy Communities: A Hybrid Static-Dynamic model

I. Martínez-Romero[1], E. Peñalvo-López [1] and I. Valencia-Salazar[1]

[1] Departamento de Ingeniería Eléctrica, Universitat Politècnica de València, Camino de Vera, 46022, Valencia, Spain
email: imarrom@etsii.upv.es, elpealpe@upvnet.upv.es, ivalencias@die.upv.es

Abstract.

The current global energy landscape is facing numerous challenges as electricity demand progressively surges: the urgent need to decarbonize generation, the increasing strain on aging transmission infrastructures, and the complex integration of intermittent renewable resources. In this scenario, Renewable Energy Communities (REC) are emerging as promising assets to achieve energy security and face increasing electricity prices. However, as RECs are still developing, there is a lack of a standardized applicable framework for the allocation of the benefits derived from self-consumption. In this work, a hybrid allocation model is developed to distribute the benefits among members of a REC based on two main pillars: type of ownership and electricity demand. The model is designed to be tailored to the own interests of the community: social equity, return on investment or self-consumption, among others. Through simulations on a mathematical model, it is verified that the final annual cost of electricity is lower than the baseline standard framework for REC.

Key words Renewable Energy Communities, Energy Allocation, Energy Security, Distribution factors, Shared Self-consumption.

1. Introduction

Today's energy sector is characterized by a complex scenario contemplating a progressively growing electricity demand occurring alongside rapid technological innovation. However, this environment is equally defined by significant challenges, specifically the volatility of energy market prices, the need to reduce dependence on fossil fuels and ensure access to reliable resources. This evolving landscape not only changes how energy is produced; it also creates the framework for new socio-economic models of energy governance [1]. At this stage, prosumers are rising and building energy communities (EC), one powerful asset with potential and space to grow [2].

Energy Communities provide a decentralized and local energy model, fostering self-consumption in diverse contexts of social conditions, location, income, energy use, etc. Through a collective environment, these entities offer a pathway to mitigating exposure to energy risks and gain independence in electricity supply at the distribution level. Moreover, they may resort to contributing to the use of renewable energy sources as Renewable Energy Communities (REC), decarbonising the localities in which they are established; this option is becoming increasingly attractive, particularly in the case of photovoltaic power, which benefits from favourable projections regarding reduced module costs, efficient system performance, and widespread social acceptance [2].

Specifically for REC, they are defined by The Council of European Energy Regulators (CEER) as entities located in the proximity of the renewable energy installations developed by the REC that possess the capacity to produce, consume and sell renewable generation [3]. Moreover, the EU Directive 2018/2001 introduces them as legal entities [4] but does not establish distinct rules for the distribution of the benefits within a community. Consequently, the absence of a universally agreed-upon allocation method has led to different regulatory interpretations across countries [5]. Within the Spanish regulatory framework, individual REC are granted autonomy to establish their own internal energy-sharing principles with the agreement of all community members [6]. Commonly adopted distribution criteria include proportional matching to overall demand, allocation based on contracted grid capacity, or distribution shares corresponding to the initial capital investment [7]. They also heavily depend on the nature of the entity, specifically whether it falls under public (e.g., municipal) or private ownership.

Reviews analysing trends regarding research on this subject conclude that despite growing interest from developed countries in implementing this organization, the majority of the studies focus on technological implementation and aggregate economic feasibility [8]. Moreover, while current literature relies heavily on optimization algorithms for benefit allocation [9] [10], it often lacks the integration of specific individual parameters to guide the allocation strategy.

This research aims to develop a comprehensive framework that defines the portion of locally generated energy credited to each REC member and evaluates the resulting economic benefits. The model is based on a hybrid allocation that integrates a mixed distribution coefficient: a static and a dynamic factor. The study models the energy system through a case study using static and dynamic allocation strategies, where the core methodological challenge consists of determining the specific distribution coefficients for each approach. This framework sets the base for balancing capital recovery with demand-side flexibility but can be tailored to the specific interests of each REC, modifying the main parameters of the model: prioritize social aspects, supporting vulnerable members; economic efficiency, regarding individual investment, and equity, ensuring fair access to energy regardless of investment capacity.

The main output of this work is the comprehensive analysis of how the distribution of the benefits (direct, as economic remuneration, and indirect, as savings for consuming self-generated energy rather than energy from the grid) affects each individual member of the REC in terms of economic aspects and energy coverage.

The paper consists of the following sections. Section 2 details the method framework, outlining the mathematical formulation of the core operational parameters. Next, Section 3 presents the simulation results derived from an applied case study. Finally, Section 4 includes the concluding remarks.

2. Methods

The model allocates energy in two stages.

The static allocation assigns a portion of the energy strictly determined by each member's financial investment in the renewable installation. This structure allows users to secure access to a specific generation designated for investors. The share of this coefficient is defined as the exact percentage of the contribution; this way, a member covering 5% of the total expenditure would be entitled to 5 % of the allocated electricity for this group of members.

The energy designated for dynamic allocation extends to all members of the REC, regardless of their investment status. This mechanism operates on an hourly basis. It is designed to dispense the rest of the generation, maximizing self-consumption rates within the REC. This way, the remaining electricity is assigned proportionally to the specific consumption needs of each member compared to the community's total unmet demand.

While investors do not directly pay for the energy received from the static allocation, electricity from the dynamic allocation is exchanged at a price ranging from grid feed-in rates and market prices for all members participating in it. Finally, the surplus generated electricity is injected into the grid, and investors receive the economic compensation associated with it proportionally to their investment share. The method does not alter the aggregate financial benefit of the REC. Instead, it redesigns the distributive system, deciding how the global benefit is divided among members and how it impacts each member.

Figure 1 includes a diagram illustrating the operational dynamics of the community.

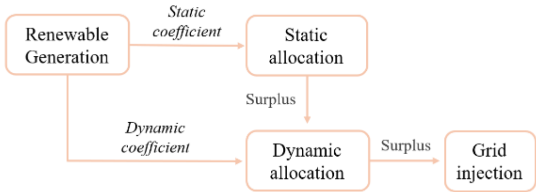

Figure 1: Energy flows within the Renewable Energy Community

This work focuses on a grid-connected energy community, assuming that the main grid provides backup power to ensure supply security during periods of low renewable generation.

A series of simulations have been performed within the MATLAB programming environment, using the following datasets.

1. Solar and wind generation data. A year of hourly renewable generation has been retrieved from historical meteorological data for a selected location in Spain. The data from solar power has been adjusted to a typical use of solar panels, with 14% losses and optimized slope and azimuth for the chosen location. Likewise, wind power has been set for the selected turbine capacity.
2. Energy consumption data. Individual household load curves are modelled computationally via *LoadProfileGenerator* [11], whereas commercial demand patterns are extracted from sector-specific reference guides.
3. Market price data. A dataset with hourly electricity market prices and injection tariffs of 2024, obtained from the Spanish electricity system operator (REE).

The work utilizes the following input variables for the mathematical model. For each hour *i* and member *j* of the REC:

σ	generation designated for static allocation (%)
G_i	renewable generation profile (kWh)
BD_{ij}	baseline consumption profile (kWh)
α_j	investment in renewable energy installation (%)
δ_j	binary variable. $\delta_j = 1$ if $\alpha_j > 0$; $\delta_j = 0$ if $\alpha_j = 0$
$PVPC_{ij}$	electricity market prices (EUR/kWh)
PIN_{ij}	electricity injection tariffs (EUR/kWh)
ρ	internal pricing weighting factor (%)

The following sections define the static and dynamic allocations through mathematical modelling of their core parameters as well as the economic architecture of the community. Lastly, an applied case study is analysed.

A. Static allocation modelling

Firstly, a portion of the generated energy is distributed according to the fixed coefficient σ. Equation 1 calculates investors' remaining demand after this stage. If the baseline demand of member *j* is greater than the electricity they receive, member *j* then takes part in the dynamic allocation. Otherwise, the surplus energy (Equation 2) is redistributed in the following step.

Investors' Residual Demand (IRD)

$$IRD_{ij} = \delta_j \cdot BD_{ij} - \sigma \cdot \alpha_j \cdot G_i \qquad (1)$$

Surplus from Static Allocation (E_{SS})

$$If\ IRD_{ij} < 0, E_{SS_i} = \sum_j \left(-IRD_{ij}\right) \qquad (2)$$

Equation 3 determines the remaining requirements of each community member.

Individual unmet demand (E_{UD})

$$E_{UD_{ij}} = \delta_j \cdot IRD_{ij} + \left(1 - \delta_j\right) \cdot BD_{ij}\ ;\ for\ IRD_{ij} > 0 \quad (3)$$

B. Dynamic allocation modelling

The energy volume designated for the second allocation stage comprises two distinct components: the generation share defined by the complement of σ, and any unconsumed surplus cascading from the initial static distribution. Therefore, Equation 4 quantifies the total energy pool available for the dynamic allocation.

Energy for Dynamic Distribution (E_{DD})

$$E_{DD_i} = (1 - \sigma) \cdot G_i + E_{SS_i} \qquad (4)$$

Next, after applying the last distribution mechanism to fulfil as much of the unmet demand as possible, the model derives the final residual demand. Equation 5 represents the definitive volume of electricity each member must procure from the external grid. This value results in grid exports (Equation 6) or imports (Equation 7), depending on whether or not member j has fully met their demand with renewable energy.

Residual Demand from Dynamic Allocation (RD_{DA})

$$RD_{DA_{ij}} = E_{UD_{ij}} - E_{DD_i} \cdot \frac{E_{UD_{ij}}}{\sum_j E_{UD_{ij}}} \qquad (5)$$

Net Grid Export (NGE)

$$If\ RD_{DA_{ij}} \leq 0, \quad NGE_{ij} = -RD_{DA_{ij}} \qquad (6)$$

Net Grid Import (NGI)

$$If\ RD_{DA_{ij}} > 0, \quad NGI_{ij} = RD_{DA_{ij}} \qquad (7)$$

This way, it is possible to calculate the portion of demand covered by both the static and dynamic stages, as shown in Equations 8 and 9, and Equation 10, respectively.

Static Coverage (E_{SC})

$$E_{SC_{ij}} = BD_{ij} - IRD_{ij}\ ;for\ IRD \geq 0 \qquad (8)$$

$$E_{SC_{ij}} = BD_{ij}\ ;for\ IRD < 0 \qquad (9)$$

Dynamic Coverage (E_{DC})

$$E_{DC_{ij}} = \delta_j \cdot \left(IRD_{ij} - NGI_{ij}\right) + \left(1 - \delta_j\right) \cdot \left(BD_{ij} - NGI_{ij}\right) \ (10)$$

C. Economic architecture of the community

With the energy allocation resolved, this section transitions to the economic settlement of the community framework. The financial model evaluates how the previously determined energy shares dictate the final distribution of economic benefits, actively balancing external grid consumption costs against the monetary value of demand covered by the REC.

Participants of the community derive financial value through three economic streams: direct savings from self-consumption, financial returns from the dynamic allocation, and grid compensation for injected surplus. To discourage speculative behaviour, the economic model intentionally maximizes the profitability of direct self-consumption. Consequently, investing members are structurally incentivized to synchronize their demand with generation hours rather than exporting their energy to the community pool or the external grid.

Electricity received through the dynamic allocation mechanism is priced below standard grid tariffs, yet strictly above the baseline grid injection compensation. This internal settlement price is modulated by the parameter $\rho \in [0,1]$, as formulated in Equation 11. As ρ approaches 0, the internal community price converges toward the lower injection tariff, thereby eliminating the financial incentive for capital investors to take part in the REC. Conversely, driving ρ toward 1 maximizes returns for investors but eliminates any economic advantage for non-contributing members, who would face electricity costs equivalent to those outside the REC. As a result, ρ functions as a key variable within the community's economic model.

Community Payment (CP)

$$CP_j = \sum_i \left\{\left[PIN_i + \rho \cdot \left(PVPC_{ij} - PIN_{ij}\right)\right] \cdot E_{DC_{ij}}\right\} \ (11)$$

Equation 12 and 13 calculate proceeds from intra-community exchange and grid export, respectively. For contributors, revenues generated from both internal community sales and grid injections are distributed proportional to each member's initial contribution, with the primary objective of shortening the payback period for investors.

Community Sales Revenue (CSR)

$$CSR_j = \sum_{ij} (CP_{ij}) \cdot \alpha_j \tag{12}$$

Export Revenue (ER)

$$ER_j = \sum_{ij} (PIN_{ij} \cdot NGE_{ij}) \cdot \alpha_j \tag{13}$$

Next, grid import cost is determined via Equation 14.

$$GIC_j = PVPC_{ij} \cdot \sum_{i} NGI_{ij} \tag{14}$$

Finally, the final cost balance for each participant is determined in Equation 15 by aggregating all respective economic flows: expenditures for external grid procurement and internal community energy, and revenues from internal sales and external grid exports. This metric serves as a comparative value, enabling a direct financial assessment between a member's baseline scenario as an independent consumer and/or prosumer and their new economic position within the REC. The definitive net savings are calculated following Equation 16.

Final Cost Balance (FCB)

$$FCB_j = GIC_j + CP_j - ER_j - CSR_j \tag{15}$$

Net Economic Savings (NES)

$$NES_j = \sum_{i} (PVPC_{ij} \cdot BD_{ij}) - FCB_j \tag{16}$$

3. Case study and simulation results

This last section is dedicated to evaluating the mathematical model through a case study and analysing the subsequent results.

For the applied case study, the REC is powered by a 65 kW generation system, combining a 60 kWp photovoltaic installation with a 5 kW auxiliary wind turbine. The community remains connected with the external distribution network to guarantee continuous power reliability, as there is not a battery storage system. Consequently, the aggregate generation profile of the REC is dictated by the photovoltaic input, closely mirroring the diurnal solar curve throughout the day. This predictability encourages members to match their load to generation hours.

The REC is composed of 18 participants, 14 of which are residential households, and the remaining 4 are commercial entities. Figure 2 outlines the participant profiles, segmenting the community into investing and non-investing members while detailing their respective shares of the initial capital investment. Likewise, Figure 3 and Figure 4 display the mean average electricity consumption per year for residential and commercial members, respectively. The load profiles of commercial entities exhibit overall temporal alignment with the community's photovoltaic production curve. Nonetheless, they generally have less flexibility to adapt their consumption to peak generation and still have nighttime load (e.g., refrigeration systems).

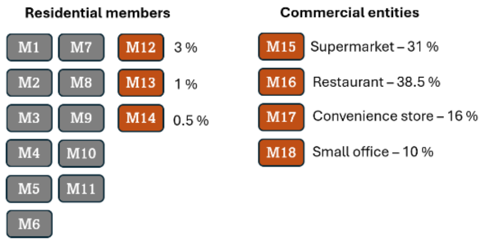

Figure 2. Renewable Energy Community member characterization

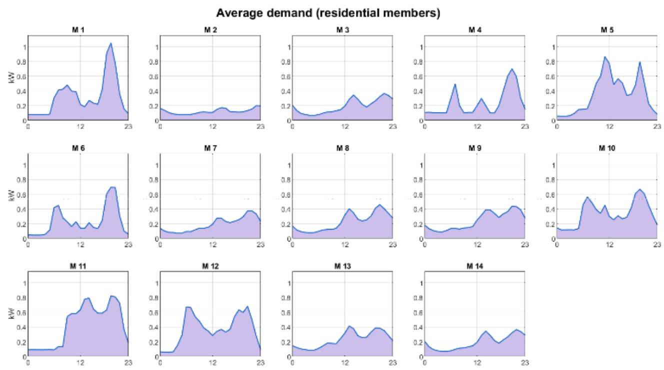

Figure 3: Average electricity demand profile for residential members

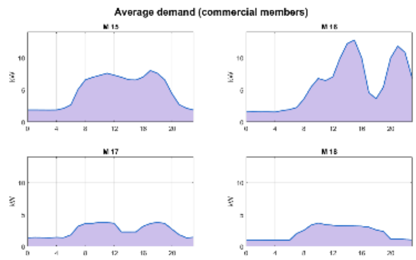

Figure 4: Average electricity demand profile for commercial entities

For the foundational analysis of the case study, the operational parameters are set at a midpoint: σ = 0.5 for the static allocation and ρ = 0.5 for the pricing coefficient. This neutral configuration allows an objective evaluation of the hybrid allocation framework's core mechanics.

First, the physical energy balances are analysed in Figure 5. Due to its high capital investment and baseline demand, commercial participants achieve a self-sufficiency rate approaching 50%, sourcing nearly half of their electricity requirements directly from the REC. Regarding residential household participants, members 13 and 14 secure a comparatively higher volume of energy during the dynamic allocation stage. Because their minimal investment yields a low static allocation, they enter the second stage with substantial unmet demand, which inherently prioritizes them to receive part of the remaining available energy. Conversely, member 12 exemplifies the inverse scenario. Because its capital investment is oversized relative to its baseline consumption, the initial allocation effectively covers its energy demand, thereby eliminating its priority during the subsequent dynamic distribution phase.

In the absence of an energy storage system, a member's capture of renewable energy depends on its demand-generation coupling. This operational reality occurs organically, even though the underlying allocation mechanism distributes energy strictly based on the ratio of individual demand to aggregate community demand. This is demonstrated with members 4 and 5. While the former concentrates its energy demand during the late evening hours and therefore only receives a small portion of electricity, member 5 exhibits a diurnal load profile and secures more than half of its consumption from the REC.

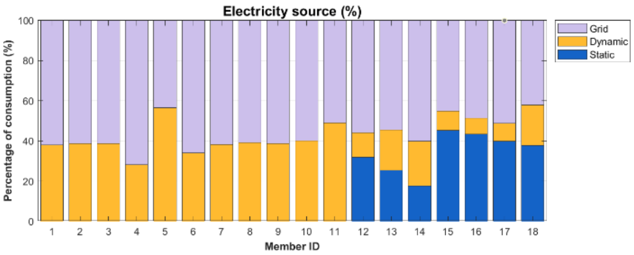

Figure 5. Evaluation of electricity source per member

The model is now compared through individual yearly FCB in two scenarios: the initial scenario with the standard REC framework with an investment-based allocation, and finally the proposed hybrid model (Figure 6 and Figure 7). For comparative baseline purposes, it is essential to note that under a standard allocation framework, electricity is distributed exclusively among the initial investors (members 12-18) while having identical generation infrastructure to the hybrid case study. Consequently, these members derive their primary economic return from injection a substantial energy surplus into the grid. Under this conventional baseline, the aggregate community self-consumption ratio sits at just 62.36 %. In contrast, the proposed hybrid model achieves 72.66 %.

As seen in the results, every member benefits from the proposed model except member 12; as stated above, its economic contribution is slightly large relative to its energy requirements and would achieve a superior financial yield under a traditional allocation scheme. This scenario highlights the importance of aligning financial contributions to baseline consumption profiles.

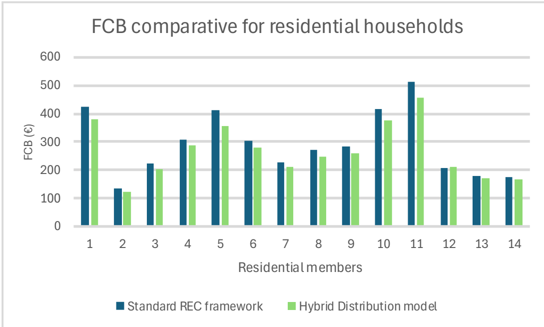

Figure 6: Final Cost Balance comparison between standard REC allocation method and Hybrid Distribution model for residential members

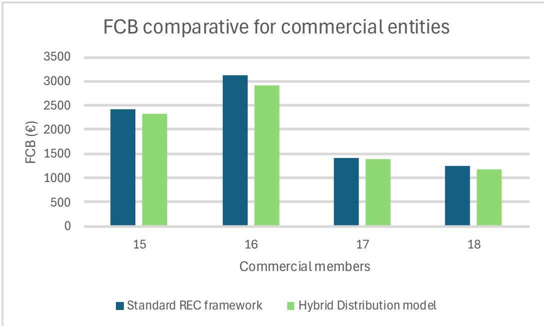

Figure 7: Final Cost Balance comparison between standard REC allocation method and Hybrid Distribution model for commercial entities

4. Conclusions

This work presents an analysis of a hybrid static-dynamic allocation model for REC. The primary objective is to evaluate how the distribution of benefits, derived from local renewable generation and collective self-consumption, impacts individual participants within a heterogeneous user base.

The study establishes a set of distribution criteria for the distribution process, which can be tailored to each REC's interests and goals. The findings suggest that the proposed hybrid allocation constitutes a middle point between the often-conflicting objectives in a Renewable Energy Community of financial profitability and self-consumption rates. By leveraging member heterogeneity, the system creates a mutually beneficial synergy by aiming for rapid return on investment for economic contributors while guaranteeing affordable energy access for non-investors. In this matter, the architecture of the allocation framework allows users to determine their own level of capital participation, effectively eliminating prohibitive financial barriers to entry. Consequently, the advantages of taking part in REC remain accessible to a broader, more diverse demographic and support energy security in local communities.

Although the model modulates individual allocations through operational parameters σ and ρ, the aggregate performance of the REC remains invariant. Because total system self-consumption, grid exports, and global economic savings are constant, adjustments to the distribution factors serve strictly to redistribute financial value among individual members.

The results show a significant reduction in electricity cost compared to baseline scenarios while actively contributing to a localized, renewable energy model. Ultimately, the proposed hybrid methodology provides a scalable scheme for the design of REC. This way, the model extracts higher value from the community's renewable capacity, protecting its members from exposure to retail market volatility and progressively bridging the gap toward grid independence.

Future research could explore the integration of additional incentive mechanisms, such as demand response-based criteria to explicitly encourage members to shift their load profiles toward peak renewable production hours. Following this line, future studies could develop a methodological criterion to evaluate the integration of new participants into an existing REC to ensure that its inclusion does not negatively impact the community. Additionally, subsequent studies should investigate the physical grid impacts of grid-connected communities under different distribution schemes.

Acknowledgment

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