Assessment of the different energy distribution coefficients in a real case energy community

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ABSTRACT

Energy Communities (ECs) were recently incorporated into European regulation with the completion of the "Clean Energy for All Europeans" (CEEP) Package. Following this, Spain transposed these new regulations in RD244/2019 and RD23/2020, providing a legal framework favorable to individual and shared self-consumption. Hence, the need to analyze the best operational way and to maximize their potential and profitability arises.

For this purpose, this work develops a model to assess the impact of different distribution coefficients and peer-to-peer (P2P) model between EC participants, on the energy and economic outputs of an EC performance. The model is tested through a real case study in the urban area of San Sebastian, northern Spain, consisting of 4 households (consumers) and one SportsCenter with PV powerplant (prosumer).

Results show that the EC's self-sufficiency and self-consumption percentages increase by 5% when the production of the EC is adjusted to the demand of its participants and are no longer fixed, this improvement is even higher for the energy savings, increasing by up to 20 % in the best-case scenario. The best results for the EC are obtained for the variable coefficients and the P2P model.

Keywords: Energy community; photovoltaic solar energy; energy transition; self-consumption; distribution coefficients.

1. Introduction

Climate change and the environmental unsustainability of energy systems are global problems and therefore the change of energy model has to be made at a global level. Addressing the global challenges of climate change and the environmental unsustainability of existing energy systems demands a comprehensive transformation of the energy model on a global scale. However, it's crucial to recognize that this transition carries a distinct local dimension and will present unique challenges in varying contexts, be it in developing, emerging, or industrialized countries.

Energy communities (ECs) serve as a critical driver of the transition to a more sustainable and decentralized energy model. They empower citizens, small businesses, cooperatives, and local entities[1]to actively participate in addressing climate change and reshaping the energy landscape. By facilitating the participation of new actors in a historically technical and economically dominated sector, ECs promote the development of an energy model rooted in local involvement [2]. Regardless of their specific definitions and regulatory frameworks, all ECs share a common aim: to explore alternative ways of organizing and governing energy systems at the local level. They become a potent instrument to ensure the new energy model aligns with the fundamental principles of energy governance, including decarbonization, decentralization, and polycentricity.

ECs contribute significantly to decarbonizing the energy system by promoting renewable energy technologies and energy efficiency, extending their impact beyond renewable generation to include education and awareness campaigns. They champion a decentralized energy system, favoring local energy generation close to demand sources and enabling self-consumption[3]. Moreover, ECs exemplify polycentric governance by emphasizing citizen participation and local decision-making, acknowledging that a blend of bottom-up initiatives and top-down support is crucial to create an effective and coherent governance framework[4]. In essence, energy communities represent a paradigm shift in energy generation and distribution, focusing on community well-being, environmental sustainability, and economic resilience [4].

Energy communities (ECs) have evolved into novel paradigms for public participation in the energy transition since the 2000s[1], with Europe leading the way, and countries like Australia, the United States, and Canada also playing significant roles[5]. However, the degree of recognition and deployment of EC initiatives varies substantially across Europe, particularly between Northern and Southern European countries, owing to historical legal ambiguities. It was only in 2016, after decades of renewable energy development strategies in Europe[6], that the European Union formally incorporated ECs into its legislation via the Clean Energy for All Europeans (CEP) legislative package, introducing Citizen Energy Communities (CECs) and Renewable Energy Communities (RECs) as distinct designations with convergent definitions[7]. This legislative recognition marked a pivotal development in unleashing the potential of ECs in advancing the energy transition.

Within the energy communities, there are different ways of distributing their energy, through distribution coefficients or P2P models.

- **Distribution coefficients**: These coefficients are pivotal within the Energy community as they determine the allocation of the shared energy to each participant. Denoted as βi, these coefficients, specified in the participant agreement, must also be communicated to the energy distribution company for consumption tracking. They can be fixed or variable, contingent on factors like individual contracted power, financial contributions to photovoltaic installations, and other mutually agreed-upon elements. Notably, the sum of all participants' coefficients should equal 1 for equitable energy distribution. The operation of these coefficients may vary by country, as in Portugal and Spain, where they must be defined and communicated to the Distribution System Operator by the managing entity[8][9], and changes to these coefficients are subject to specific regulations, including a 12-month minimum adjustment period.

- **P2P model:** P2P is a decentralized model where individuals collaborate using their available resources to create, trade, or distribute goods and services, transcending the energy system and redefining how society engages in service and commodity exchange. This innovative approach is already manifested in real-world applications, like public bicycle sharing and peer-to-peer car sharing, and more recently, in vehicle-to-grid storage systems[10]. The P2P model for electricity trading, initially proposed in 2007, has since materialized in various pilot projects, such as the renowned Brooklyn Microgrid endeavor[11]. This model offers advantages in terms of fairness and transparency, as it facilitates exchanges within a collaborative economic framework, potentially resulting in reduced electricity costs for participants and higher self-consumption rates of locally generated renewable energy. P2P markets come in various forms, including centralized community-based markets and distributed bilateral trading markets, yet in many countries, regulatory constraints still restrict direct energy exchanges among prosumers. Nevertheless, there is a growing movement to adapt these regulations and realize this novel vision for energy markets, with tools like Grid Singularity, an open-source energy technology company, playing a crucial role in simulating such energy communities.

In Spain, the distribution of energy within ECs is currently confined to fixed or static distribution coefficients. However, for more flexibility and efficiency, dynamic distribution coefficients are an optimal approach, although their implementation is still pending. The authorization for dynamic distribution coefficients can be granted through ministerial orders, as per the 5th final provision of RD 244/2019 [12]. Notably, RD 244/2019[12] introduced various changes, including defining self-consumption variants from individual to collective, with all participants in the latter adhering to the same self-consumption modality and providing a signed equality agreement to the distributor or using contracted power as the basis for distribution if no agreement is reached.

The regulation goes on to outline different self-consumption modalities, distinguishing between those with or without surpluses. Those with surpluses have further subdivisions, including surpluses subject to compensation, where simplified compensation mechanisms are introduced. These changes aim to make distribution coefficients more adaptable, allowing variations on an hourly basis rather than fixed values for billing periods. Despite the lack of clear legislation, it is imperative to recognize the eventual shift toward dynamic and variable coefficients in the framework of energy communities [7].

In this context of evolving regulations and undefined community energy frameworks, the fair distribution of energy resources among community members is a vital consideration. Distribution coefficients play a pivotal role in energy allocation within these communities. Optimizing these coefficients is essential for efficient utilization of renewable resources, improved energy system efficiency, and waste reduction[13]. Researchers have proposed various optimization techniques, including mathematical programming, stochastic modeling, and evolutionary algorithms, to maximize the economic and environmental benefits of energy communities. Moreover, the emergence of machine learning [14]offers new opportunities for optimizing distribution coefficients by analyzing complex energy data, predicting demand and supply patterns, and enhancing energy allocation based on multiple parameters.

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2. Methodology

This work developed an EC model to assess the impact of considering different distribution coefficients of locally generated renewable energy within energy communities, analysing energy and economic indicators. The energy community modelling was performed for a real case study in San Sebastian, in Spain. Figure 1 presents the methodology flowchart.

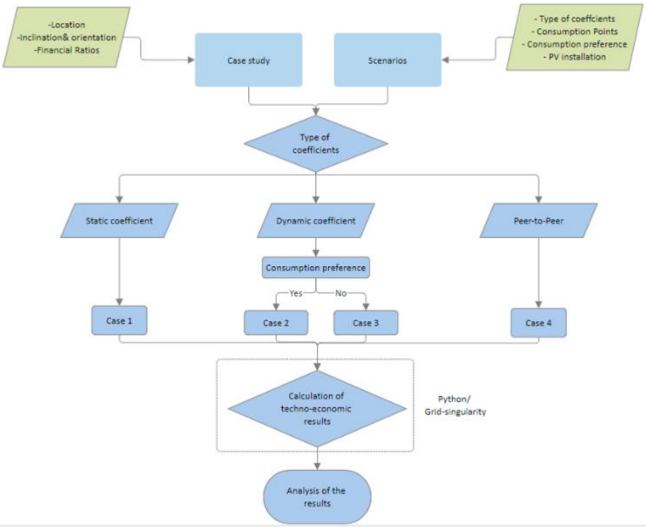

Figure 1. Diagram of the methodology designed to analyze the EC.

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Case	**Prosumer priority on sharing**	**Distribution coefficient**	**PV sizes installed**
1	x	Fixed	5, 10, 15 kW
2	x	Variable	
3		Variable	
4		P2P market	

Table 1. Description of the cases to be studied.

The methodology commences with the delineation of the case study and its diverse scenarios, primarily defined by the characteristics of the energy community (EC), encompassing its location, size, the number of participants, their load profiles, and the capacity factor of the photovoltaic (PV) installation. The analysis of the EC model focuses on several key aspects, including the cost of energy, individual household savings, self-consumption rates, and self-sufficiency rates. It involves an hourly comparison between the power allocated to each participant and their actual demand to ascertain whether all demand can be met or if a power deficit or surplus occurs. In cases of surplus or shortfall, the grid intervenes to balance the excess or shortfall, which influences the EC's electricity expenses, providing a critical evaluation parameter for different scenarios.Data utilized in the model includes synthetic demand data generated with LoadProfile and user-specific information, while PV generation data relies on hourly capacity factors calculated using PVsyst software.

The model assesses performance over the course of a year, reporting economic metrics (cost of energy and savings) and energy metrics (self-consumption and self-sufficiency rates) for comparison. However, it should be noted that these metrics do not encompass potential year-to-year fluctuations or account for financial risks or electricity price volatility.

2.1. *Scenarios*

The energy community studied in this paper is composed of 4 consumers and 1 prosumer. The cases studied are described below

- Case 1 the distribution coefficients are fixed and equally distributed, being the same to every household. The coefficients are determined by a contract between the participants of the energy community, the estimated distribution percentages for this first case is 25% to each house.

- Case 2, where the distribution coefficients (DC) are going to be variable depending on the consumption of each participant every hour and giving preference to the household with greater demand.

- Case 3, where the DC are going to be variable depending on the consumption of each house and adjusting the distribution proportionally to the hourly demand, not prioritizing any house in specific.

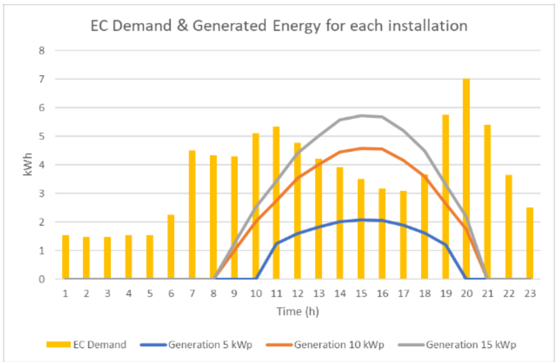
- Case 4, peer to peer distribution simulated in the Grid Singularity LEM software.

2.2. *Case study*

- *Geographical location:* The project involves placing a photovoltaic generation facility on the roof of the Manteo municipal sports center in the city of San Sebastian. As stipulated in RD 18/2022 the users of the EC must be located at a distance of less than 2000 meters from the point of electricity generation.

- *PV installation:* The system has a solar photovoltaic installation on top of the sports pavilion (prosumer) with 4 residential household (consumers) connected in the energy community.

- *Demand*: For the demand 4 people at each site was contacted and considering their profile we simulated their consumption on the Load Profile software when there were not sufficient data to make the simulation. The consumer profiles are a Student Flat-sharing, a family with two children, a Single parent with two children and a family with 1 child.



Graph 1. EC Demand & Generated Energy for each installation throughout a day

- *Tariff prizes:* For the Tariff prices, this study takes the tariffs imposed on June 2021 in Spain. The tariff regulation that went into effect on June 1st altered the volumetric rates of electricity depending on the hour of the day. The objective was to decrease peak consumption by encouraging consumption during historically low hours. However, the new tariff regulation increases the volumetric prices for peak hours (midday and early at night) and decreases them during valley consumption hours (late at night). That's why prices for both periods (P1 and P2) are taken into account. The hours in which the different periods apply are reflected in Figure 7 where the "Peak" Tariff refers to P1 and the "Valley" Tariff to P2.

Figure 2. Chart of the hours that correspond to each period.

For the periods above the prizes are 0.027€/kWh for P1 and 0,02 for P2.

- For the techno-economical data of the PV installation a 20 year lifetime has been estimated, the cost per kW installed is 1.033€, and the operational cost is 10€/kW/year and all this with an interest rate of 3 %.

2.3. *Grid singularity case study*

Since the software imposes the inputs to perform the simulation in a certain way, this section explains how these inputs have to be interpreted so that the case is as similar as possible to case 1, 2 and 3 allowing a comparison.

- Production: The different capacity of the PV is imposed (5,10,15 kW)
- Demand: The profiles chosen for the study are, for house 1 the "Family 2 children profile", for house 2 the "Flatsharing student" profile, for house 3 the "Retired Couple" profile and for house 4 the "Young Couple". In the case of simulating the behavior of the Sport Center we have chosen the "6 apartment building" and added 2 more loads to reach a similar consumption of the Sport Center. And we have also added the generation at this point where the installed power will be changed for the different scenarios.

The key distinction in the Grid Singularity modeling lies in the energy market model used for sharing within the energy community. Unlike cases 1-3, where predefined distribution coefficients and energy sharing incurred no transaction costs, case 4 adopts a peer-to-peer (P2P) energy trading approach, entailing associated transaction costs. To integrate the necessary values for the Grid Singularity Energy Community's energy market, an annual average of hourly prices from the original case study is computed to yield a single value. The terms in the model, including the selling rate (representing the community's purchase of energy deficit from the external grid), the buying rate (signifying the external grid's acquisition of surplus from the community), and the grid fee value (reflecting grid fees for market trading), are defined and refined to provide a comprehensive overview of the trading dynamics. These modifications enable a more in-depth assessment of the community's energy market performance and costs, contributing to a refined analysis of the case.

2.4. *Key Performance Indicators*

To derive valuable and meaningful insights from this study, a set of key performance indicators (KPIs) will be employed to assess and compare the distinctions between Fixed and Variable coefficients and the P2P model. These KPIs are thoughtfully selected to provide a comprehensive evaluation encompassing both economic and energy savings for the Energy Community. The following KPIs have been chosen:

- **Self-sufficiency**:

self-sufficiency (EC) = self-consumed energy/ total energy demanded

- **Self-consumption**

self-consumption (EC) = self-consumed energy / total energy produced

- **Energy cost**
  - *SportsCenter Energy cost = Energy consumption*

*(kWh) * Energy price(€/kwh) – Surplus energy-not shared (kWh) * Surplus selling price (€/kWh)*

- *Consumers Energy cost from grid= Energy consumption (kWh) * Energy price(€/kWh)*

- *Consumers Energy cost from EC= Energy consumption (kWh) * Grid tariff (€/kWh)*

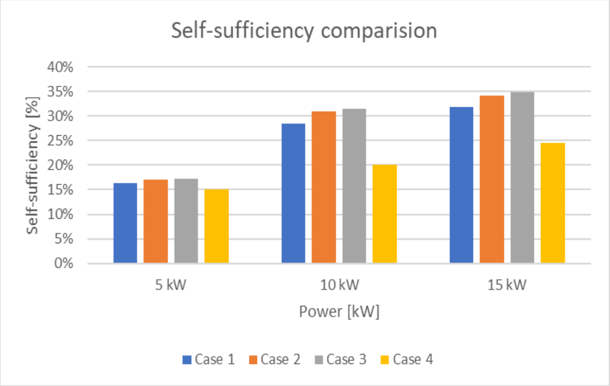
- **Payback**

PB= Initial PV installation investment / Cashflow (Energy cost savings, Operational costs)

There are many business models of energy communities and how to obtain economic benefit from them, but for this case study, it has been estimated that the energy community is public, so all the investment is going to be made by the city council in the rooftop of the municipal sports center. This implies that the houses that consume the energy of the prosumer will only pay the price of the grid tariff. On the other hand, the prosumer does not receive any money when he shares his energy in the EC, so it is likely that the payback increases when the energy is shared with the other houses, and he acts as a prosumer. All of this is covered by the equations seen in this section.

3. Results and discussion

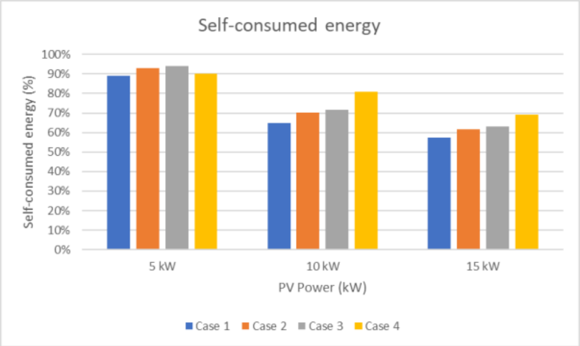
3.1. *Self-sufficiency*



Graph 2. Comparison between cases in terms of the Self-sufficiency

When comparing the 4 cases in terms of self-sufficiency, it can be seen that for the first three cases the percentage of this KPI is higher than the one of the simulation with Grid singularity. This difference in percentages is due to the fact that the simulations made with Python takes into account the production and demand of the EC over a whole year and per hour. On the other hand, case 4 the self-sufficiency is the lowest, that can happen because for this EC case members have the ability to set their own energy prices, which can vary based on supply and demand dynamics and that affects directly to the distribution and the preferences of each EC. This difference may also be due to the fact that the data are not the same after all, as the grid singularity consumption profiles are simulations that may vary slightly from the house profiles of the first 3 cases. However, for the other cases it can be seen how the percentage of the KPI increases, this is due to the fact that by modifying from a fixed coefficient to a variable coefficient distribution, increases the self-sufficiency by enabling more efficient and tailored energy allocation among the four houses, reducing the need for external energy and optimizing energy distribution to better match changing community needs in real-time. This results in less energy waste, decreased reliance on external energy sources, and a higher proportion of locally generated energy being consumed.

3.2. *Self-consumption*

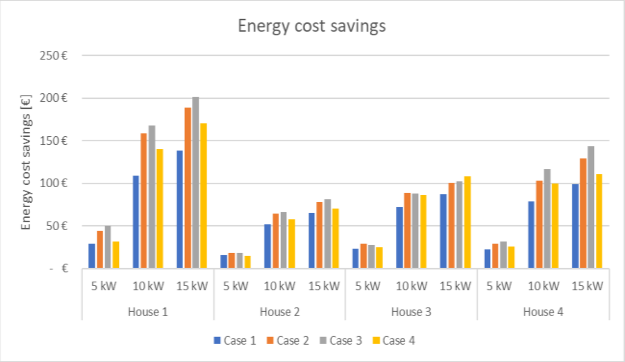


Graph 3. Comparison between cases in terms of the Self-consumption

When approaching the comparison of this KPI, it is important to remember that it measures the capacity of the EC to self-consume what it produces. As we can see in the graph, for case 1 the percentage is lower than the other two cases, this is due to the fact that the energy self-consumed is not the maximum because the distribution coefficients are fixed. This makes sense because as it has been said if you impose that each house consumes an exact amount of the energy produced, there will be a house that at certain times is not needing it and will pour it to the grid when there is another house that would need that energy at those times, so for case 1 is losing energy produced from the prosumer because the energy distribution is not optimal. For case 2 and case 3 the percentages of self-consumption are very similar also to the percentages of the Grid singularity because although the energy distribution of Case 2 gives preference to the house that consumes the most energy, the energy generated will always be self-consumed to the maximum because the distribution coefficients are variable, this implies that whenever there is production to meet the demand, it will be distributed all without having to evacuate one of the houses excess of energy to the grid, because it first checks if all the houses are satisfied energetically. For case 3, the EC allows a more efficient response to fluctuations in energy generation and consumption, ensuring that the surplus energy is channeled where it's needed most at any given moment, that results in the highest self-consumption of the first 3 cases. In the case of Grid singularity which simulates the operation of the peer-to-peer EC, although the management of the EC can be complicated, it offers a high degree of flexibility, allowing members to adapt to changing energy needs, pricing, and market conditions. This makes self-consumption the maximum for these cases.

It should also be noted that the percentages of all cases decrease as the power of the installation increases, this is due to the fact that throughout the day more energy is produced than can be consumed. For energy communities with higher demand than production, the self-consumption will be higher because everything that is produced will be consumed resulting on a higher percentage of the self-consumption KPI.

3.3. *Energy cost savings*



Graph 4. Comparison between cases for the energy cost savings.

When analyzing the energy savings it can be seen that the more energy is produced, the "cheaper" energy each house gets and consequently the more it saves during a year. This phenomenon occurs for each house.

On the other hand, when comparing by type of distribution coefficients, it can be seen that if we keep these coefficients fixed (Case 1), the monetary savings in terms of energy consumption is lower because the energy that is being produced is not being correctly distributed and may receive more energy than necessary, leading to unnecessary external energy purchases.

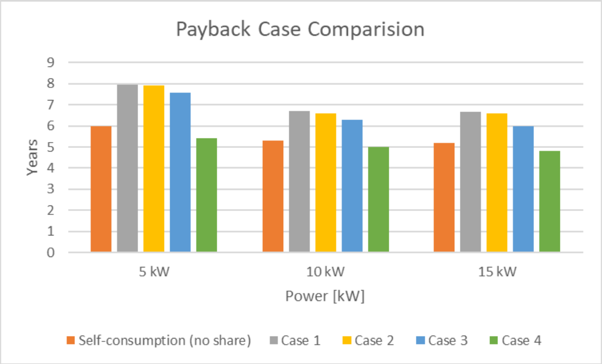
With a variable coefficient (Cases 2 & 3), the community is more likely to be able to meet its energy needs internally, using locally generated energy. This reduces dependence on external energy purchases, which in turn increases the savings as it can be seen in the graph. This can be seen directly by comparing the blue columns with the orange or the grey ones. If the distribution coefficients are variable, the monetary savings of the houses increase due to an energy distribution that adjusts to the demand of the houses.

As for the comparison of case 2 and case 3, it can be seen that case 3, apart from being a fairer distribution of energy (because it distributes the energy proportionally to the demand), it generates more savings for all the houses, and it is even more noticeable in the houses where there is more accumulated consumption. This is due to the fact that for case 2 there will be moments in which the houses with lower consumptions will have high punctual consumptions and the houses with higher accumulated consumptions will become secondary to perceive the energy surplus. Case 2 turns out to be detrimental to all households as it does not distribute the energy proportionally every hour.

For case 4 the savings are more fluctuating depending on the consumer and each installation, since being a P2P case, each energy community will obtain different results depending on the preferences of each one. For this particular case it can be seen how all consumers save less than with a distribution coefficient EC except for the case of house 3 of the 15-kW installation. However, it is important to note that in P2P communities, members can set their own energy prices, which can vary according to the dynamics of supply and demand.

3.4. *Payback*

If we analyze the comparative graph, we can see how the payback is barely reduced with respect to the type of coefficients used, this is because as it has been explained before the payback focuses on the investment made by the SportsCenter. This payback is reduced in the case of the P2P energy community, as several variables come into play that make the prosumer increase his income from the sale of energy to both consumers and the grid.



Graph 5. Comparison between cases in terms of the Payback.

It is noteworthy to mention that to calculate the payback of an energy community, many variables have to be taken into account and can vary greatly depending on how the business model of each one is made. For this case study we try to maximize the savings of the consumers, this means that they only pay the grid tariff for using the distribution network and the prosumer does not benefit from it. The consumers also do not contribute to the initial investment in the PV installation, which generates greater savings but higher costs for the sport center. These scenarios have been set out to demonstrate what consumers would save with the help of public energy communities subsidized by governments, i.e., with no investment costs. For private ECs, consumers would have to pay an initial investment or an extra monthly fee to the prosumer.

In brief, the specific payback period will vary depending on the economic circumstances of each energy community.

4. Conclusions and Future Work

This work started with the objective of technically and economically assessing the best way to share energy between users of a EC. To this end, a specific methodology and model has been developed in order to evaluate which options are most favorable to the economic prospects of the EC, in addition to their degrees of self-consumption and self-sufficiency. This model simulates an EC with an hourly time resolution for a full year so that it is able to evaluate the economic impact of variations in the grid price, the demand curves throughout the year and the management that is carried out of the energy of energy surpluses in the EC.

The model was applied to a case study in the city of San Sebastian using real household and SportsCenter consumption data. In addition, the use of static distribution ratios, as reflected in the current rules, has been compared with variable distribution ratios and a P2P model in order to assess the impact of making ECs more flexibles. The results obtained show that the EC's self-sufficiency and self-consumption percentages are increase by 5% when the production of the EC is adjusted to the demand of its participants and are no longer fixed, either by making the fixed coefficients variable or by using the P2P model. This improvement is even higher for the energy savings, increasing by up to 20 % in the best-case scenario. The best results for the EC are obtained for the variable coefficients and the P2P model.

Although it is important to note that the payback for these cases is not reduced by the same percentage as the savings, this is due to the assumption that the investment in the solar installation corresponds to the prosumer, but this assumption can be modified for another study and make all participants contribute an initial investment, which would generate a lower payback. Another option could be to increase the prosumer's revenue by charging a monthly/annual fee from the consumers, such as P2P which considers the energy exchange between neighbours paying amounts of money directly to each other. That is why the payback of the P2P model (Case 4) is the shortest of all.

Energy community projects have a lot of potential to advance towards a more sustainable and fairer energy transition as shown by the literature. However, this potential needs to be understood by the society to make the right efforts and investments. Therefore, one of the first recommendations to be made to the ECs would be to implement models such as the Variable coefficients or P2P model so that users can be given economic security and profit at the moment of joining this kind of projects.

For those reasons the use of variable coefficients is recommended to achieve a better match between production and demand. However, the current regulatory framework does not yet allow the use of variable coefficients and the actual framework only contemplates updating the fixed ones once a year. Therefore, a recommendation for the ECs is to lobby public bodies to achieve a favourable and stable regulatory framework that provides certainty, clarity, and predictability to the development of ECs. To have an impact in this area, collaboration between the different energy communities will be important in order to achieve synergies that favour all those who embark on these projects and encourage the entry of new ECs. Collaboration between people will be essential to achieve a human-scale and fair energy transition.

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