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A fair dynamic incentive allocation method for virtual energy sharing in renewable energy communities that rewards members' virtuosity and engagement

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ABSTRACT

The development of renewable energy communities is essential for the energy transition and is strongly supported by European policies promoting local renewable energy initiatives. However, implementing fair economic allocation methods remains a significant challenge, as these must maximize the benefits of local renewable generation and encourage efficient electricity sharing. Addressing this issue is necessary for advancing the effectiveness and equity of renewable energy communities across Europe.

This work proposes a novel economic incentive model aiming to equitably allocates rewards among users in electricity-sharing initiatives. The method uses a reward system based on daily evaluations of two factors: a similarity factor, measuring each user's alignment with renewable generation profiles, and a utilization factor, assessing the renewable energy exploited to meet their load.

A case study of four members in a standard Italian multifamily residential building demonstrates the model's effectiveness. Results show that users' virtuous behaviours positively impact energy efficiency and economic returns. The findings highlight this method's potential to enhance community engagement, foster cooperation, and drive renewable energy adoption.

This study provides a robust framework integrating economic principles with renewable energy use, showcasing the viability of innovative incentive mechanisms to promote equitable, sustainable energy practices and support the global energy transition.

1. Introduction

The pursuit of sustainable energy solutions has become a global priority, with a focus on collaborative and community-driven approaches. In this context, energy communities have emerged as a transformative resource with a critical role to contribute to the ongoing energy transition. According to the latest data from the European Commission, renewable energy communities have experienced significant growth in recent years [1] thanks to the positive legislative background promoted by the European Commission through the Renewable Energy Directive II (RED II) [2] and its recent third update (RED III) [3]. As of 2022, there are over 2250 registered energy communities or cooperatives projects across Europe [4], marking an impressive +50 % increase from 2018 [5]. This impressive growth highlights the increasing momentum and recognition of energy communities as important players in the transition towards sustainable energy systems integration [6]. The European Union's commitment to promoting community-led renewable energy projects is evident both in its legislative frameworks, within the Fit For 55 Package under the European Green Deal [7], but also in the economic support that encourages the promotion of energy sharing projects [8]. This attitude is greatly influencing the development and spread of energy communities, reflecting a positive response to the supportive legal environment [9].

The legislative frameworks have greatly improved community involvement in renewable energy projects by providing incentives and support mechanisms. These provisions enable communities to actively participate in generating and distributing renewable energy, while also addressing financial barriers through favourable financing conditions, grants, and other incentives [10]. The legislation promotes a variety of energy community models, such as cooperatives, local energy-sharing initiatives, or joint ventures [11]. This allows communities to choose structures that best suit their objectives, but at the same time generates a very diverse and sometimes complex framework for defining an energy

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Nomenclature

Symbols

E	Energy
f	Factor
p	Power
η	Utilization factor
θ	Similarity factor
I	Incentive
r	Incentive rate
t	Time

Subscripts/superscripts

all	Allocation
ex	Export
g	Generation
im	Import
l	Load
lgc	Locally generated and consumed
m	m-th member of community
M	Total number of community members
sh	Shared

Acronyms/abbreviations

ARERA	Italian Regulatory Authority for Energy, Networks and Environment
CE	Community Energy
DSO	Distribution System Operator
EU	European Union
IoT	Internet of Thinghs
LEC	Local Energy Community
P2P	Peer-to-peer
POD	Point of Delivery
PV	Photovoltaic
REC	Renewable Energy Community

community [12].

1.1. Defining energy communities

The scientific literature on energy communities reflects a diversity of definitions and acronyms, highlighting the complexity of this concept. Variations such as "Renewable Energy Community (REC)", "Local Energy Community (LEC)", "Community Energy (CE)" and "Energy Cooperative" are commonly used, each capturing distinct characteristics and nuances. The lack of a straightforward definition for energy communities arises from the complicated nature of these entities [13]. Energy communities involve a spectrum of structures, ranging from traditional cooperatives to emerging local energy-sharing initiatives. Furthermore, diverse regional contexts and evolving energy landscapes contribute to the semantic variability surrounding energy communities [14]. The nature of an energy community can be traced back to several key characteristics that affect its configuration.

Legal structure. Clarifying the organizational structures and operational models of energy communities and its members is an essential starting step. This involves understanding the distinctions between cooperatives, joint ventures, and other community-led initiatives.

Scope. The formation of energy communities is driven by various purposes, which introduce a layer of variability. While some communities aim for a financial return on their energy investments, others prioritize the shared use of energy resources or seek to achieve cost savings collectively. Defining the diverse purposes and motivations behind energy communities is fundamental to capturing the spectrum of their objectives within a comprehensive definition [15].

Table 1
Key variables for defining an energy community.

Community variables	Properties to define
Legal structure	Clarify diverse models such as cooperatives, local energy-sharing initiatives, joint ventures, etc.
Purpose	Define the community's goals, whether profit-making, shared energy use, cost savings, avoiding emissions or a combination.
Size	Consider the scale, whether it's an apartment block, city block, or an entire district.
Shared resource	Specify the type of energy resource focused on, such as electricity, thermal energy, or a combination of both.
Economic model	Define ownership structures, revenue distribution mechanisms, and financial models.

Size. The size of a community, whether it is an apartment block, city block, or an entire district, is a significant factor that requires careful consideration. The scale of the community not only affects its organizational structure but also impacts the level of participation, resource management, and overall objectives.

Shared resource. The complexity of energy communities is further increased by the shared energy resources within them. These resources can include electricity, thermal energy, or a combination of both. Recently, there has been a growing interest in photovoltaic energy communities, which focus on the sharing of electricity. However, it is important to note that there are other forms of shared energy resources beyond photovoltaic energy [16].

Economic model. Defining the economic aspects of a community, such as ownership structures, revenue distribution mechanisms, and financial models, is necessary for a comprehensive understanding. This includes how costs and benefits are shared among community members.

The definition of each feature, summarized in Table 1, generates a unique energy community entity. It is important to clarify each characteristic unambiguously before approaching this topic.

1.2. Goals and open challenges for energy communities

The objectives that can be pursued through the establishment of an energy community are multidisciplinary and embrace different energy, economic and social aspects.

On the energy front, communities aim to decentralize energy production by shifting from large-scale centralized facilities to localized, community-led generation. Additionally, there is a strong emphasis on promoting renewable energy adoption to reduce dependence on conventional, non-renewable sources, enhancing energy independence at the local level. Energy sharing, a fundamental key goal of the community, generates energy savings that consequently result in environmental sustainability [17].

Economically, energy communities seek financial benefits by realizing returns on their energy investments. This may involve revenue generation through the sale of excess energy or cost savings for community members [18]. Furthermore, the establishment of energy communities contributes to local job creation, providing opportunities related to the planning, installation, maintenance, and management of community-led energy projects.

From a social perspective, energy communities prioritize community empowerment by involving members in energy decision-making processes and ownership. This approach fosters a sense of empowerment and collective responsibility. Additionally, energy communities

Table 2
Goals and open challenges of energy communities.

Dimension	Goals	Challenges
Energy	• Decentralized energy production • Renewable energy adoption • Energy/emission savings	• Integration of emerging technologies • Nationwide gird balancing • Effective energy flexibility management
Economic	• Revenues streams • Utility bill savings • Local job creation opportunities	• Economic incentives/institutional support • Navigating changes in business models • Risk of financial appropriation
Social	• Community empowerment • Community resilience • Social cohesion and collaboration	• User perception, education, engagement • Administrative management • Job integration and new skills • Occupation of urban space

contribute to building community resilience by ensuring a more reliable and sustainable energy supply, especially in the face of external shocks. Social cohesion and collaboration are also included, as communities work together towards shared energy goals, strengthening social bonds and promoting a culture of shared responsibility [19].

Alongside the many positive goals and ambitions that energy communities strive to promote and pursue, there are, however, important challenges that slow down and sometimes limit their development and deployment.

On the energy side, integrating new technologies and managing energy flexibility opportunities are ongoing challenges [20]. Balancing decentralized energy flows within communities with regional or national energy networks requires careful coordination to ensure stability and reliability [21]. Economically, overcoming financial barriers often requires economic incentives and institutional support [22]. Navigating the transition in business models, particularly in a sector dominated by multi-energy utility companies, is complex [23]. Energy communities must strive to establish equitable models that ensure fair allocation of benefits among community members, avoiding the risk of financial appropriation by larger entities [24]. On the social front, user perception, education, and engagement are critical factors for the success of energy communities. Educating users and community members about this novel form of energy initiatives is important for building awareness and gaining positive community participation [25]. Moreover, simplifying administrative processes and integrating new jobs and skills into the community are essential for efficient management and sustainable growth. In urban areas with high energy demand and limited space, spatial challenges are also a significant factor. To effectively address the additional spatial requirements of decentralized generation technologies, careful urban planning and integration are necessary to optimize land use [26].

Overall, it is clear that while energy communities offer significant opportunities, they also face various challenges across three main dimensions: energy, economic and social. These challenges are dynamic and require strategic approaches to unlock the full potential of energy communities. Table 2 provides a comprehensive overview of the opportunities and challenges still facing energy communities, categorized by energy, economic, and social dimensions. These aspects should always be addressed together, without no one dimension taking precedence over the others.

1.3. Objective and structure of the work

Within the broad energy, economic and social context that characterises the energy community sector, this paper aims to address a specific open challenge by proposing an innovative method of allocating the economic benefits generated by energy sharing among the members of a community. Fair allocation of incentives – a common issue across various European national legislations – is not only relevant for the economic development of communities but also fundamental for enhancing member participation, awareness, and engagement. An overview of the current state-of-the-art methods employed for incentive distribution is presented in Section 2. Subsequently, in Section 3 the paper introduces an innovative method designed to ensure a fair allocation of incentives generated by shared energy flows within the community. The proposed method aims to balance economic considerations while increasing the members' involvement inside the community. To illustrate its practical application, this work employs a case study involving a small community of 4 members within the Italian context, presented in Section 4. The findings and discussions from this application, gathered in Section 5, offer insights into the effectiveness and implications of the proposed incentive allocation method, contributing to the wider debate on enhancing the sustainability and community benefits of energy communities.

The main contributions of this work are: (i) the development of a novel incentive redistribution method that introduces a dynamic weighting mechanism based on daily similarity and utilization factors, promoting energy "virtuousness" within the community; (ii) the integration of social engagement and economic equity into the incentive model, extending beyond purely financial optimization; and (iii) the numerical validation of the approach within an Italian energy community context. This work brings novelty to the current literature by combining dynamic energy performance indicators with a fair allocation logic, offering a replicable framework aligned with European policy needs.

2. A review on the possible allocation strategies in community streams

Within energy communities, economic incentives take different forms, reflecting the diverse nature of these initiatives. Incentives can include financial returns from energy generation, shared revenue from excess energy sales, reduced energy costs for community members and other economic benefits derived from community participation [27]. In addition, new forms of incentives include financial contributions that reward a community's ability to share energy, even virtually without a physical exchange of energy [28]. In this context, the literature has tried both to understand the different sources and forms of incentives and to propose and develop innovative allocation schemes.

In 2021, Casalicchio et al. [29], developed a community benefit-sharing method based on a member's participation in the community, exploiting auction and game theory. The authors defined a Fairness Index (FI) based on the evaluation of the Gini Index [30] to assess the contribution of each member within the community in terms of energy exchange and economic expenditure. The lack of cost allocation methods for community energy was also highlighted by Li et al. [31], who explored more than 10 different methodologies for allocating economic benefits and expenses in 2022. The authors concluded that methods based on energy flows perform better than methodologies based on energy composition and prices because they correctly reflect user behavior. In a recent study by Lilliu et at [32]. a game-theoretic approach was applied to incentivize members in a peer-to-peer community energy market, rewarding self-consumption and renewable production. The application on real data showed an increase in user-generated benefits and self-consumption. Game theory was also applied by Wang et al. [33], proposing a scheme of cooperation between community members to overcome conflicts of interest and allocating economic benefits by forming coalitions between members. Some studies have instead focused on the incentivisation of electricity peak-shift as a premium parameter. Penalty algorithms to avoid large fluctuations in community electricity consumption have generated

Table 3
Methods schemes for economic incentive allocation in energy communities.

Allocation Method	Description
Proportional sharing	Allocates incentives based on individual contributions or investments, ensuring proportionality.
Equal sharing	Distributes incentives evenly among community members, regardless of their individual contributions.
Voting systems	Involves community members in the decision-making process, allowing collective decisions on incentive allocation.
Needs-Based allocation	Considers the scoial/economic circumstances of members, allocating incentives according to their needs.
Performance-based allocation	Links incentives to the actual performance of community energy projects, fostering a results-oriented approach.
Hybrid models	Combine multiple methods for a balanced approach that considers both individual contributions and community welfare.
Blockchain technology	Emerging trend using smart contracts for transparent and decentralized incentive distribution.

interesting results in cost-saving and profit-improving [34]. In this context, Zhao et al. developed special indices to assess power fluctuation and measure grid stability as a function of community energy behaviour [35]. The authors showed that minimizing or maximizing these indices in a multi-objective optimization function can significantly reduce community energy costs. Finally, recent literature suggests a growing interest in exploring blockchain technology for transparent and decentralized incentive distribution [36]. Blockchain-based smart contracts can automate and ensure the transparency of incentive allocation processes, providing an innovative solution to enhance trust and fairness within peer-to-peer energy trading [37].

Across European states, the distribution of economic incentives in energy communities is influenced by national legislative frameworks [38]. These frameworks often define the types of incentives and the criteria for their allocation. Common incentive categories include Feed-in-Tariffs (FiTs), premium payments, tax incentives, and grants for community projects based on renewables [39]. The allocation quantities are typically tied to the allocation criterion used by the legislative scheme. In most cases FiTs are associated with the energy flow exported from the community to the regional or national grid. Grants and tax incentives, on the other hand, are often linked to initial investment or new job creation. However, more interesting are mechanisms that incentivize specific premium factors. Here the quantities incentivized with premium payments can be very widely disparate, such as peak power on the grid or energy shared within the community [40].

The use of incentives for specific quantitative variables within a community is usually associated with allocation methods that fall under the category of “Performance-based” strategies. These methods value and reward specific performances achieved by the community or its individual members through specific actions. This type of allocation is particularly interesting for research purposes as it allows for the structuring of specific allocation strategies based on the community’s purpose. For completeness, Table 3 summarizes all current methodological incentive allocation structures used in established energy communities.

In conclusion, the literature on economic incentive allocation in energy communities reflects a dynamic field where various methods are being explored to balance individual contributions, community welfare, and socioeconomic considerations. Current literature shows that the incentive and revenue stream allocation models of energy communities are multiple and often generated according to specific objectives [41]. This paper aims to introduce an allocation method that can fairly value the commitment and participation of members in consuming and sharing energy based on the needs of the entire community by rewarding virtuous behaviour. The proposed method focuses on shared energy, which is the physical quantity incentivized. This concept is based on the definitions contained in the incentive schemes promoted by the European Union and implemented by Italian legislation.

3. Methods

To properly develop a method for allocating an economic incentive generated among the members of an energy community, Section 3 is structured as follows. Section 3.1 frames and positions the proposed approach, highlighting its scope and assumptions. Section 3.2 then describes the energy community modeling approach, detailing the energy flows and balance considerations. Finally, Section 3.3 outlines the detailed allocation method, presenting the evaluation of the allocation factor and its use in the determination of individual rewards.

3.1. Method framework and assumptions

Based on the framework presented in the previous sections, the proposed method falls among the performance-based methods and defines the incentive allocation for energy communities of any legal structure and size whose purpose is to share energy from renewable sources, preferably electricity, given the simplicity of its transport and dispatch. To better contextualize the positioning of the method described in this section, it is necessary to consider the following points.

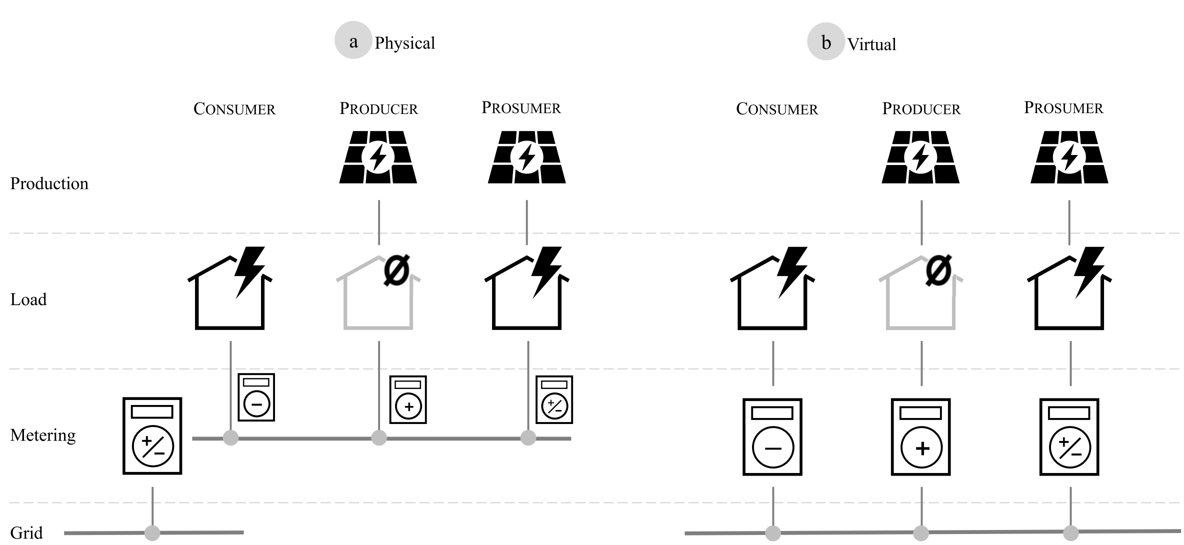

Fig. 1. Physical (a) and virtual (b) configuration schemes for an energy community made up of consumer, producer, or prosumer members.

- The objective of the allocation method is to provide a fair allocation that promotes social development and can reward the energy virtuousness of members, in response to the open economic and social challenges of an energy community (see Table 2)
- The allocation method requires that there is an incentive scheme for energy shared among community members. This quantity is in fact identified as the incentivized variable.
- The energy sharing scheme should be virtual. This means that the community's energy sharing capacity is evaluated through an ex-post economic incentive. In a physical energy sharing scheme, there would be no need to incentivize this capacity, as members would benefit directly from it (as explained in the following paragraph).

With regard to the last point and restricting the analysis to PV-based energy communities, two main technical arrangements that enable energy sharing can be identified: physical and virtual [42]. A physical self-consumption scheme (Fig. 1a) involves a direct connection between community members through an infrastructure that allows behind-the-meter sharing of the energy produced, without generating any impact on the grid. In this configuration, the point of delivery (POD) between the community and the grid is unique, and members are responsible for accounting their own energy flows.

In the virtual self-consumption scheme (Fig. 1b), the exchange of energy among members involves the use of the grid, which at first accounts for the energy flows generated by each member, and only later, virtually, will associate the energy-sharing capacity among community members (each of whom corresponds to a single POD). In this configuration, physical exchanges of energy continue to exist but take place over extensive portions of the public grid, which are usually limited to low- or medium-voltage areas.

The advantage of physical configuration is the immediate energy benefit that members can obtain through direct self-consumption of shared energy. In contrast, in a virtual configuration, the shared energy is not physically self-consumed, but remains only a quantity that, following an accounting process, can be valued in the form of an economic incentive. Virtual configuration only benefits (or sometimes disadvantages) the distribution system operator (DSO) in terms of grid balancing and energy transport. The benefits to users are, in this case, the result of economic enhancement in the form of an incentive issued by the grid operator. Furthermore, the virtual configuration offers the advantage of increased flexibility and ease of implementation. This simplifies the relationship between users and the grid operator, as each member can participate in the community without requiring any infrastructure changes to the grid. Fig. 1 schematizes the two described energy community configurations, assuming the participation of consumer, producer, or prosumer members.

3.2. Energy community modelling

In every energy community configuration, regardless of the type of its members, it is possible to identify the most significant energy flows in order to model its energy behavior. For each m-th member it is possible to identify a time-dependent generation $p_{g,m}(t)$ and load $p_{l,m}(t)$ profile, as well as the imported $p_{im,m}(t)$ and exported $p_{ex,m}(t)$ flows between the member and the outer perimeter. Fig. 2 describes the possible energy flows involved in a building, i.e. a community member. The energy balance of each member, in the time interval $t_2 - t_1$ is therefore solved by Equation (1).

$$\int_{t_1}^{t_2} p_{g,m}(t)dt + \int_{t_1}^{t_2} p_{im,m}(t)dt = \int_{t_1}^{t_2} p_{l,m}(t)dt + \int_{t_1}^{t_2} p_{ex,m}(t)dt \tag{1}$$

Equation (1) represents the most general energy balance for a building. In fact, both the generation and load profiles are only present in the prosumer case, while a consumer-only will have $p_{g,m}(t) = 0$ and a producer-only $p_{l,m}(t) = 0$. Furthermore, energy import and export are usually mutually exclusive.

A key energy flow for a prosumer is also represented by the share of power generated and locally consumed behind-the-meter, $p_{lgc,m}(t)$. This quantity, reported by Equation (2), represents the amount of self-consumed power.

$$p_{lgc,m}(t) = \min\left(p_{g,m}(t), p_{l,m}(t)\right) \tag{2}$$

Finally, in order to model energy exchange among all community members M, it is necessary to define the shareable energy flow, which is the power made available (exported) by some members that can be instantaneously consumed (imported) by others. Equation (3) defines shareable energy flow, a quantity aggregated by the whole community. Shared energy is a physical quantity that can only exist on a community basis, and is therefore evaluated based on the total number of members M belonging to the community.

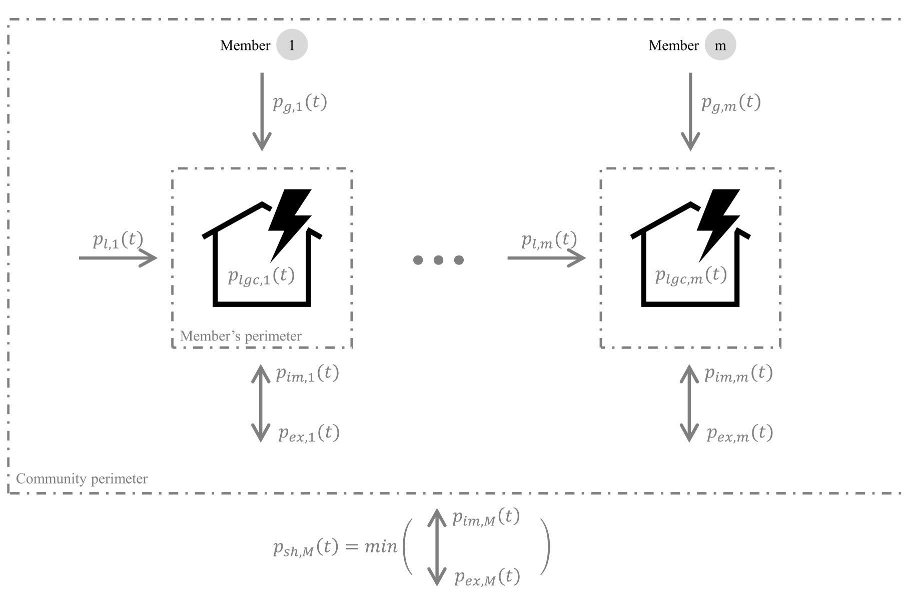

Fig. 2. Energy flows involved in energy community modelling.

$$p_{sh,M}(t) = \min\left(p_{ex,M}(t), p_{im,M}(t)\right) = \min\left(\sum_{m=1}^{M} p_{ex,m}(t), \sum_{m=1}^{M} p_{im,m}(t)\right) \tag{3}$$

The definition of shareable energy is the basis of any technical arrangement of energy community. Specifically, $p_{sh,M}(t)$ represents the amount that can be physically exchanged among members of a physical configuration, or the amount that can be incentivized within a virtual arrangement. Fig. 2 attempts to summarize the energy flows involved in modeling a PV-based energy community, visualizing the physical perimeters from the perspective of both the individual member and the entire community.

3.3. Allocation method

In the context of a community energy where the amount of energy shared virtually among members is incentivized, this section proposes an allocation method that can reward energetically virtuous behavior of its members.

The allocation method assumes the generation of an economic incentive I_M, generated by the amount of energy shared among members, as expressed by Equation (4):

$$I_M = r \cdot E_{sh,M}\big|_{\Delta t} = r \cdot \int_{\Delta t} p_{sh,M}(t)\,dt \tag{4}$$

Where r is the incentive rate, expressed in €/kWh (for the European context) and $E_{sh,M}$ is the energy shared in the Δt interval. Incentive rate (r) depends on the incentive policy, while the time interval (Δt) typically aligns with the monitoring interval used by the DSO to account for energy flows to and from users.

The allocation of the total incentive I_M, generated for the benefit of the entire community, is then allocated by normalizing an allocation factor $f_{all,m}$ characteristic of each member of the community according to Equation (5), guaranteeing each member their own recognition of the personal incentive I_m.

$$I_M = \sum_{m=1}^{M} I_m = \sum_{m=1}^{M} \left(norm\left(f_{all,m}\right) \cdot I_M \right) \tag{5}$$

Equation (6) provides the formula for calculating the allocation factor $f_{all,m}$. This factor is determined by multiplying two factors specifically defined for this work, namely the similarity factor θ_m and the utilization factor η_m.

$$f_{all,m} = \theta_m \cdot \eta_m \tag{6}$$

This method assigns specific roles to each of the two factors in assessing the energy behavior of individual members towards the community.

Similarity factor. θ_m factor studies the similarity between the energy flow consumed by the member in relation to the total generation of the community. The purpose of this factor is to assess how closely the load profile of the individual member matches the generation profile of the community. The similarity between these two energy fluxes, treated as vectors, is studied by evaluating the pairwise distance between the two sets of observations, using cosine similarity as the distance metric, i.e. the cosine of the included angle between points (treated as vectors).

The result, expressed by Equation (7), is a similarity factor in the range [0,1] that describes how similar load and total generation are. The methodology employed in this study solves Equation (7) on a daily basis, providing a daily similarity factor for each community member.

$$\begin{aligned} \theta &= \frac{x_s y_t'}{\sqrt{(x_s x_s')\cdot(y_t y_t')}} \ (\textit{general form}) \\ \theta_m &= \frac{p_{l,m} p_{g,M}'}{\sqrt{\left(p_{l,m} p_{l,m}'\right)\cdot\left(p_{g,M} p_{g,M}'\right)}} \ (\textit{specific form}) \end{aligned} \tag{7}$$

Where the vectors x_s and y_t, for the purpose of this study, are defined as the daily trend of the individual member load profile ($\Delta t = 1$ day), $p_{l,m} = \int_{\Delta t} p_{l,m}(t)dt$, and the community's generation aggregate profile, $p_{g,M} = \sum_M \int_{\Delta t} p_{l,m}(t)dt$.

It is important to specify how the cosine similarity does not take into account the absolute values of the two profiles, but only their evolution over time (day-by-day in this method). Within the proposed method, θ_m factor is evaluated daily, returning a daily similarity factor between the two vectors considered. For this reason, it is necessary to use energy time series with a time granularity less than daily, at least hourly or sub-hourly. As an illustration, Fig. 3 shows three hypothetical vector pairs of consumption and generation, highlighting their θ_m value.

Utilization factor. η_m factor estimates the amount of energy generated by the community on a daily basis that can be used by the *m*-th member to meet their load. This factor is calculated using Equation (8) and is

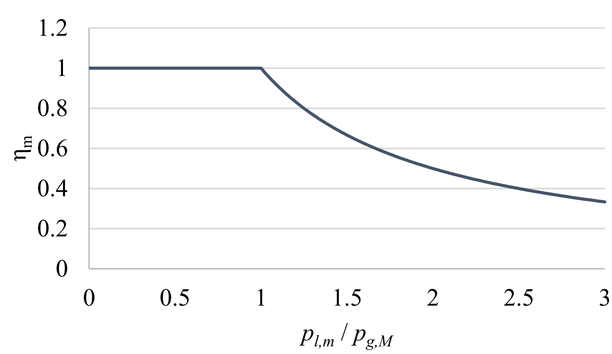

Fig. 4. Utilization factor trend as function of consumption/generation ratio.

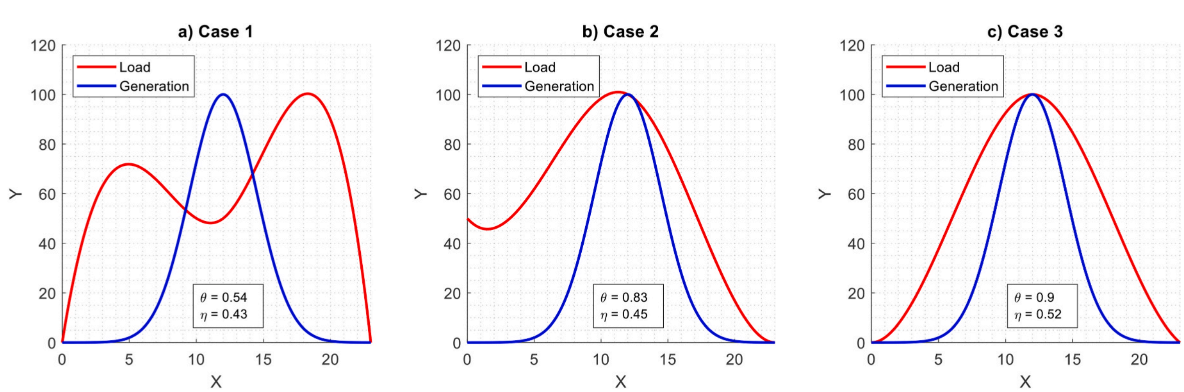

Fig. 3. Example of similarity and utilization factors evaluation on fictitious load and generation profiles for three different profile pairs.

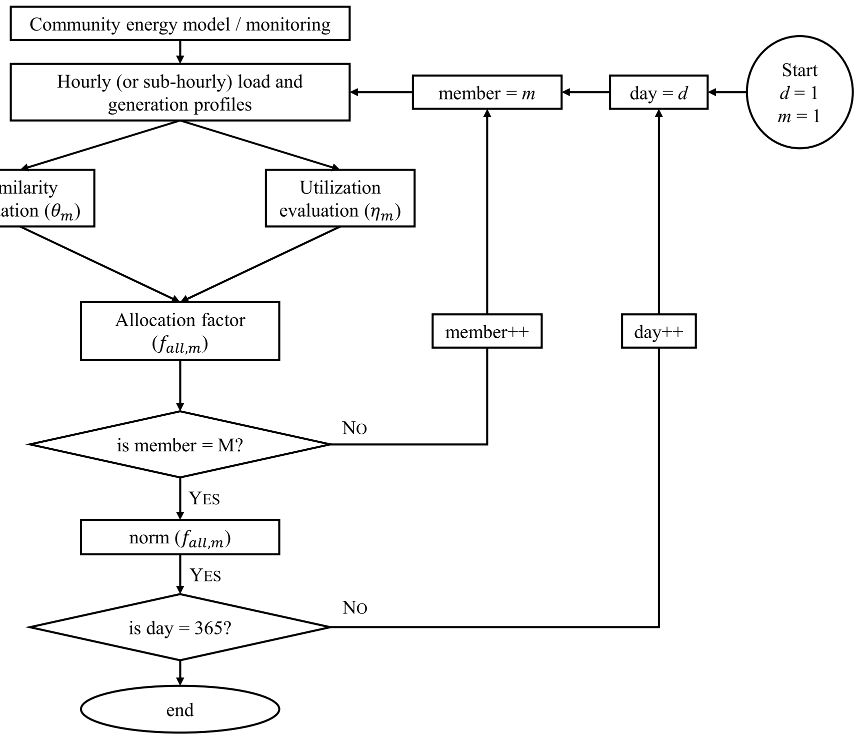

Fig. 5. Block diagram of the incentive allocation methodology proposed in this paper.

equal to 1 when the daily energy generated by the community exceeds the *m*-th member's load. However, it decreases as the daily load exceeds the community's generating capacity.

$$\eta_m = \begin{cases} 1 & \text{if} \quad \int_{\Delta t} p_{l,m}(t)dt \le \sum_M \int_{\Delta t} p_{g,m}(t)dt \\ \dfrac{\sum_M \int_{\Delta t} p_{g,m}(t)dt}{\int_{\Delta t} p_{l,m}(t)dt} & \text{if} \quad \int_{\Delta t} p_{l,m}(t)dt > \sum_M \int_{\Delta t} p_{g,m}(t)dt \end{cases} \tag{8}$$

The η_m factor rewards members who can potentially cover their daily energy needs through renewable generation, while it penalizes high demand members for whom it is easier to take advantage of the direct self-consumption of their own generation system. Fig. 3 displays the variation in η_m for different energy profiles, while Fig. 4 illustrates the trend in η_m as a function of the ratio of consumption to generation.

With this approach, the η_m factor is introduced not to discourage self-consumption per se (which remains a desirable and directly incentivized behavior), but rather to avoid disproportionately rewarding members who can easily absorb large amounts of shared energy simply because of their high overall consumption. In energy communities, it is relatively easy for high-demand users to maximize virtual sharing by increasing their consumption, thereby capturing a larger portion of shared benefits. However, this behavior, if unchecked, contradicts the core principle of sustainability that should prioritize energy savings over energy consumption. The η_m factor thus acts as a balancing mechanism: it discourages excessive energy use as a strategy to boost incentive allocation and ensures that the distribution of community benefits remains aligned with energy efficiency and fairness. This correction helps prevent large consumers from dominating the energy sharing system and promotes a more equitable and sustainable model of community participation.

The final allocation factor $f_{all,m}$, outcome of the product of θ_m and η_m, will consequently be in the range [0,1]. Physically, $f_{all,m}$ will reward community members who are able to follow the community generation profile as closely as possible (θ_m factor), but without excessive consumption relative to the community's generation capacity (η_m factor). The assessment interval for $f_{all,m}$ is daily. Therefore, the allocation algorithm generates a daily incentive allocation based on the energy flows analyzed. The final allocation of the I_m incentive is assessed by normalizing the daily allocation factors associated with each member, adopting Equation (5). The allocation methodology is schematized in Fig. 5, which summarizes all the steps that make up the incentive allocation algorithm.

Table 4
Case study community members load and PV system characteristics.

Member	User load		PV system (generation)	
	max power [kW]	yearly consumption [MWh]	peak power [kWp]	yearly production [MWh]
m1	6.0	11.08	2.0	2.96
m2	4.5	3.74	2.0	2.96
m3	3.0	2.10	0	0
m4	1.5	0.23	6.0	8.88

4. Materials

4.1. Case study setup

The presented allocation methodology was applied to a case study of a multi-family residential building in the European urban context. The building consists of four members and is part of an energy community with a virtual sharing scheme (refer to Section 3).

The selected apartment building is located in the province of Turin, in northern Italy. The building has four members, three of whom are residential users and one represents the users of the common spaces of the building, such as external lights, lift, and auxiliary utilities (with its dedicated energy meter). Each member has a different load profile, depending on the maximum withdrawal power available from the network. Additionally, three members have their own private photovoltaic generation system of varying power output, which they share with the community after self-consumption.

Using hourly electricity load profiles based on statistical data made available by the Italian Regulatory Authority for Energy, Networks and

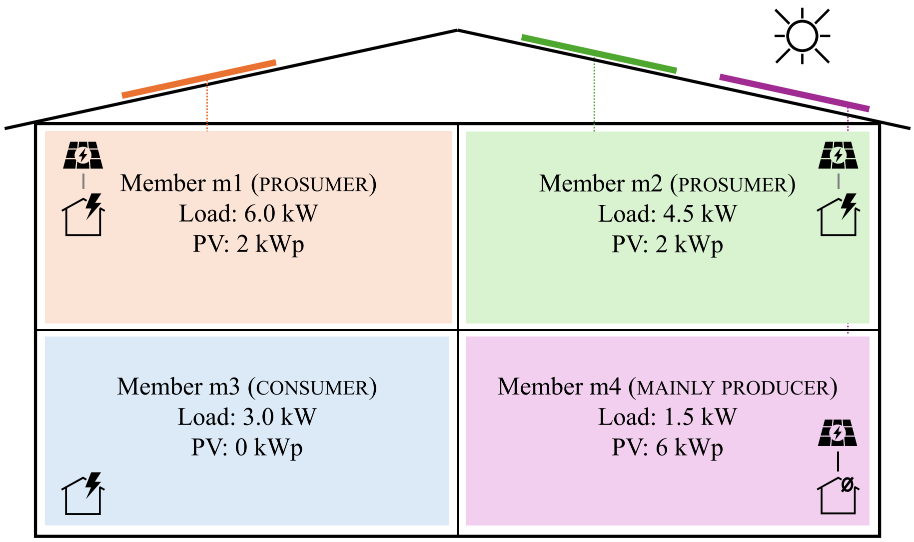

Fig. 6. Graphic representation of the case study with main technical specifications (load and generation peak power).

Environment (ARERA) [43] and simulating the hourly producibility of PV systems through PVGIS [44], hourly load and generation profiles for the reference year 2021 can be obtained. The 4 members constitute the case study energy community, with the characteristics summarized in Table 4 and the schematic representation in Fig. 6.

4.2. Benchmarking allocation methods for case study analysis

In order to assess the effectiveness of the proposed incentive allocation methodology and to provide a robust basis for comparison, five alternative allocation methods, based on both academic literature and real-world pilot projects, were implemented within the case study framework. These methods represent a wide range of strategies that are commonly found in the categorization outlined in Table 3. Each method is applied to the case study, and the resulting results are compared and discussed in the results section.

- **Allocation Method #1** – *Proposed Method*: This is the novel approach developed and detailed in Section 2, designed to promote fair and virtuous energy behaviour among community members.
- **Allocation Method #2** – *Equal Sharing*: A simple and widely adopted baseline approach, in which the incentive is divided equally among all community members, regardless of their consumption, production, or investment profiles.
- **Allocation Method #3** – *Proportional financial-based*: Incentives are distributed proportionally to each member's financial contribution to the community. For the case study, the total initial investment is assumed to be composed of 80 % allocated to PV system installation and 20 % to general establishment costs (e.g., permits, administrative tasks). The PV investment is assigned based on each member's installed capacity, while the remaining 20 % is equally distributed among all members.
- **Allocation Method #4** – *Hybrid Equal/Production-Based*: A mixed approach in which 50 % of the total incentive is allocated equally,

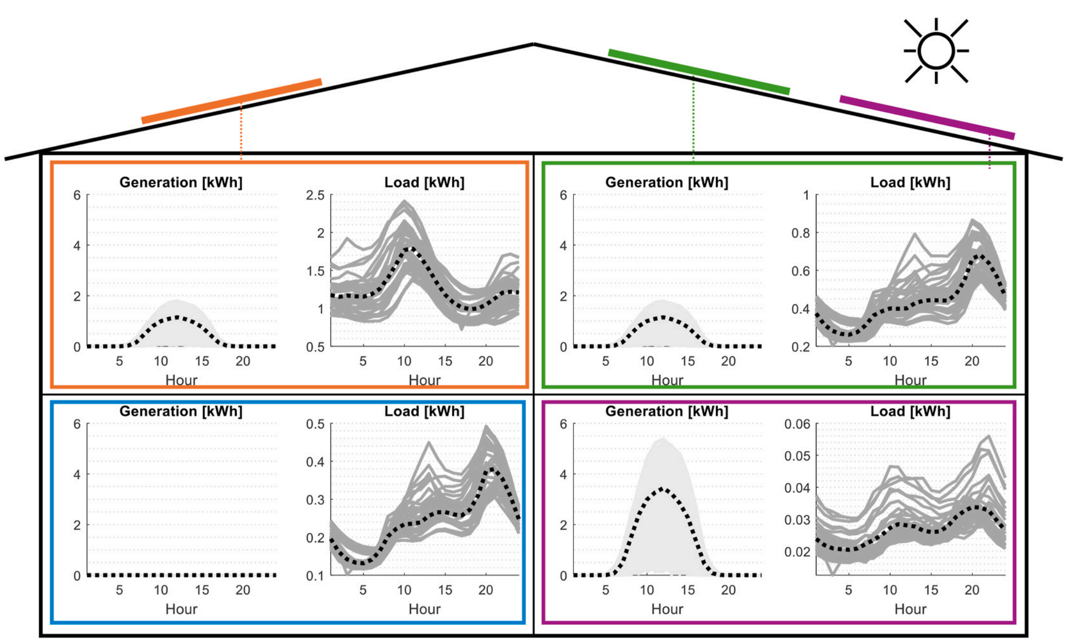

Fig. 7. Generation and load profiles of members, with average values (dashed line).

while the remaining 50 % is distributed proportionally to the individual PV system capacity installed by each member.

- **Allocation Method #5** – *Performance-Based*: Incentives are distributed based on a performance metric that rewards members who consume energy during a favourable time window for community energy sharing, specifically between 12:00 and 14:00. The allocation factor for each member is calculated by means of Equation (9).

$$f_{all,m} = \frac{\int_{\Delta t} p_{l,m}(t)dt}{\int_{\Delta t} p_{l,M}(t)dt} \tag{9}$$

where Δt represents the time interval from 12:00 to 14:00 over all days in the year, $p_{l,m}(t)$ is the load of member m, and $p_{l,M}(t)$ is the total load of all members during the same interval.

A detailed discussion on the implications, advantages, and drawbacks of each allocation strategy will be presented in Section 5.4 through a comparative numerical analysis.

5. Results and discussion

This section presents the results of the allocation method applied to the case study, examining how hourly energy flows translate into daily incentive allocation. Results cover the analysis of the energy profiles (Section 5.1), the daily evaluation of the allocation factors (Section 5.2), and the discussion on dynamic behavior over typical days in different seasons (Section 5.3). Finally, a comparison of results from applying different allocation methods is proposed (Section 5.4).

5.1. Energy flows analysis

In order to better understand the proposed allocation mechanism, some considerations on the energy flows taken into account in the allocation methodology and their physical meaning in the context of the community energy balance are necessary. Fig. 7 illustrates the generation and load profiles of each member, displaying their daily flow profiles and average annual value (dashed line). The generation profiles reflect the peak power associated with each member's PV generator, while the load profiles vary according to the statistical profile selected. The allocation method will reward the relationship between the load profiles of individual members and the generation capacity of the entire community. Taking member 1 as an example, it is evident that the load profile closely follows the generation trend. The similarity factor θ_m will consider this detail. However, this member also requires the greatest load in absolute terms. The utilization factor η_m will take this behavior into account.

The annual energy balance of the community's members is depicted in Fig. 8, which compares the energy consumption (in red) and production of each member (in yellow), also showing the share of self-consumed energy (in green). The annual balance reported in Fig. 8 was solved on an hourly basis, which is also evidenced by the calculated self-sufficiency values of each member (in grey) using the relation $p_{lgc,m}(t)/p_{l,m}(t)$. Although members m1 and m2 have the same PV generation, the value of self-sufficiency increases in the case of m2, since total consumption is lower. However, m1 shows better behavior in terms of self-consumed energy, thanks to a higher similarity between the load and generation profiles (see Fig. 7). Member m4, on the other hand, although presenting a much higher PV generation than its load, fails to achieve high levels of self-sufficiency (which stops at 47.84 %). This indicates a noticeable mismatch between generation and consumption.

5.2. Evaluation of daily allocation factors

After modelling the energy community and analyzing the flows on an hourly basis, the allocation factor f_{all} was assessed daily by solving Equation (6). Fig. 9 shows the allocation factor assessed throughout the year, along with its two components θ_m and η_m, for each member. A consistent trend in the similarity factor is noticeable for each member, with higher values during the summer months. This is because the larger summer production profile is better suited to match the load profile. It is worth noting that member m1 achieved higher similarity values on average than the other members, indicating that the load profile is generally more similar to the generation profile. As shown in Fig. 7, this characteristic enables member m1 to increase the similarity factor, indicating an energetically efficient behavior in matching the energy demand with on-site generation.

The utilization factor is almost always close to unity throughout the year. The data indicates that the community's aggregate generation systems consistently produce more energy than its members consume daily. Member 4 steadily maintains an η_4 value of 1, as their limited energy load is always met by the generation output. In contrast, member 1's higher load profile results in a different outcome compared to other

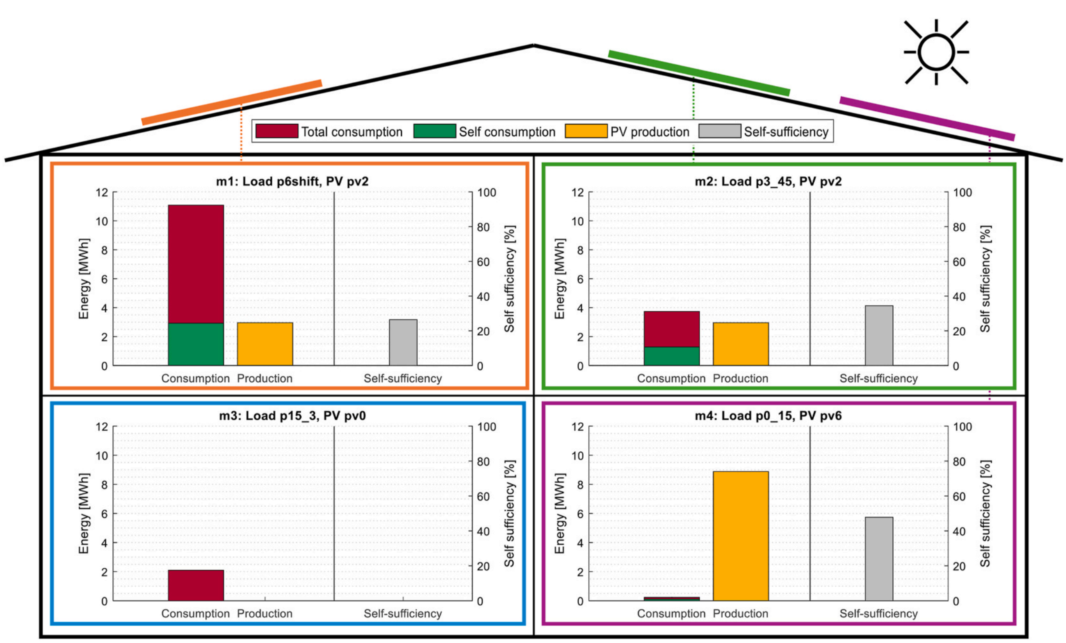

Fig. 8. Annual energy balances and self-sufficiency for community members (on an hourly basis).

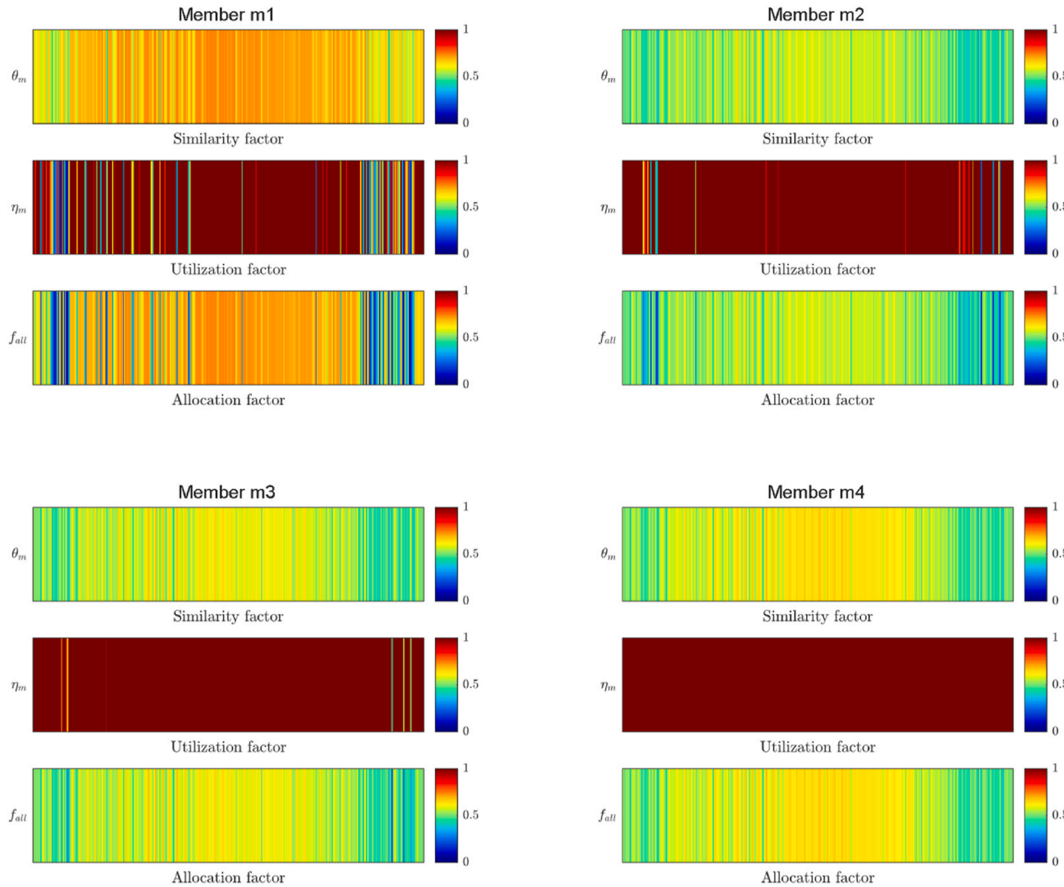

Fig. 9. Daily trend (from day 1–365) of similarity, utilization and allocation factors for each community member.

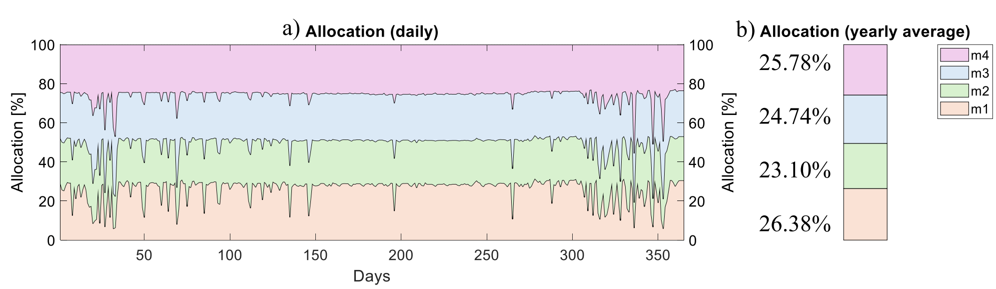

Fig. 10. Daily trend of the allocation percentage (a) and annual average results (b) for each community member.

community members. Occasionally, the energy load exceeds the energy produced by the community on a daily basis, especially during the winter season when renewable energy production decreases.

The allocation factor's daily trend determines the distribution of a hypothetical incentive on virtually shared energy. The proposed allocation method rewards members who can minimize the mismatch between demand and generation while keeping their consumption within the community's generation potential. Fig. 9 demonstrates how member 3 participates in the allocation methodology despite having no generation system. This is because the load profile has an impact on the shared energy outcome within the community, as stated in Equation (3).

The last step of allocation involves normalizing the f_{all} factors to 1, resulting in a daily percentage allocation that can be applied to community members. Fig. 10a shows the dynamic development of the normalised allocation of f_{all}. The trend in the figure follows the considerations anticipated in the previous paragraph. The impact of a lower photovoltaic producibility during the winter season is significant, causing the allocation to favor the member with the most limited load profile (member 4) compared to the others. The percentage distribution remains relatively constant during the summer season. This behavior can be attributed to two main factors. Firstly, the generation system has a high producibility and is always able to cover the load of the member (η_m factor equal to 1). Secondly, the load profiles for this case study were generated through statistical collections, resulting in low daily variability. As a result, there is not much variation in the value of θ_m from one day to the next.

Fig. 10b displays the average annual allocation value for each member. The allocation favors member m1 (26.38 %), which matches onsite production with its consumption profile better than the others. Member m4 also achieves a good allocation value (25.78 %), thanks in part to a reduced load profile. In general, community members do not deviate significantly from the average when applying the proposed allocation criterion. This can be attributed to the statistical origin of the load profiles used, as well as the limited difference between members'

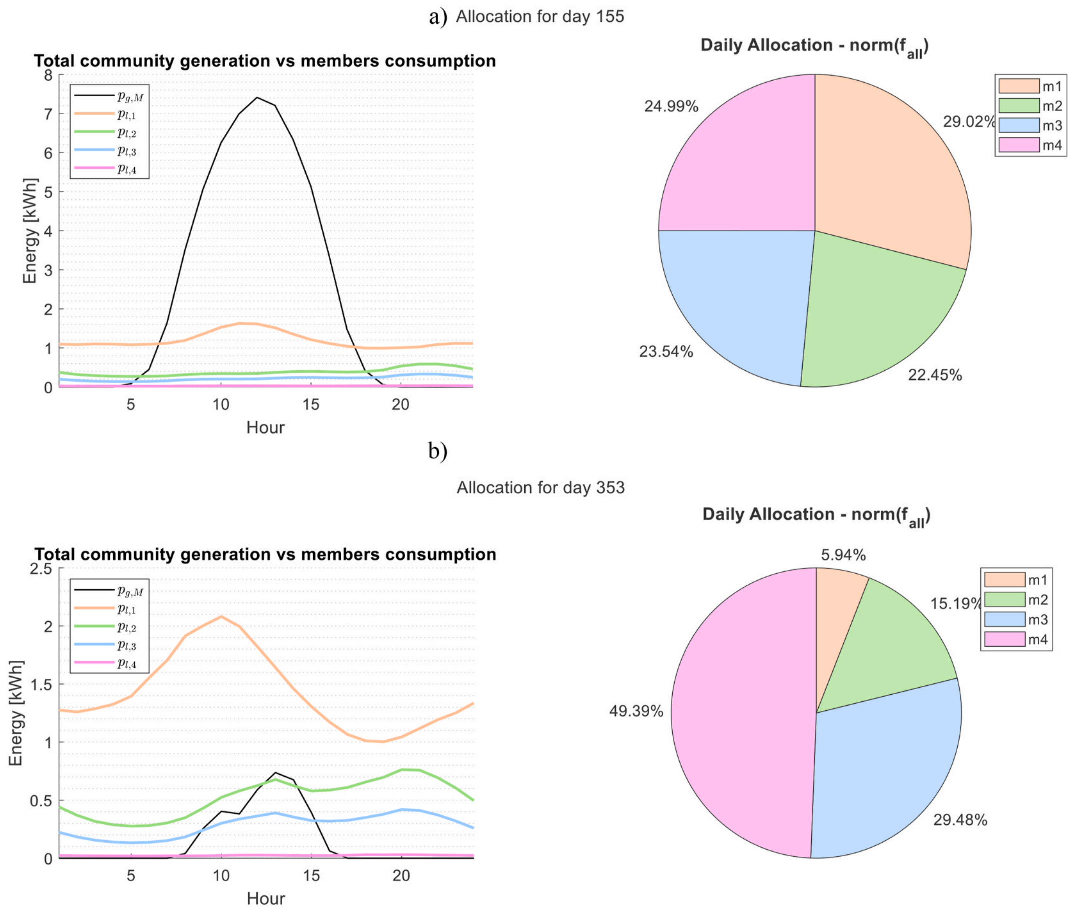

Fig. 11. Individual load and daily community generation profiles with percentage allocation for a typical summer (a) and winter (b) days.

energy profiles in absolute terms.

5.3. Impact of time dynamics on incentive allocation

To gain a better understanding of the dynamic behavior implemented by the allocation method, two typical days with opposite characteristics were examined. The daily pattern of load and generation flows involved in the evaluation of the allocation factors was studied, which subsequently led to the allocation percentage associated with each member.

Fig. 11a focuses on day 155, a typical day of the summer season, while Fig. 11b shows the study of day 353, representative of the winter season. The pie chart in the figure shows the percentage allocation results, which are quite diversified, thus confirming the logic behind the allocation methodology. In the summer case, the community's generation curve (represented by the $p_{g,M}$ energy flow) exceeds the members' load curves. The allocation result is determined solely by the similarity factor θ_m, which prioritizes member m1 to closely follow the production curve. During winter days, on-site generation is reduced, resulting in a completely opposite behavior. The utilization factor penalizes higher load profiles, while the m4 member is rewarded as the only one able to virtually cover its needs from renewable sources.

Table 5
Percentage incentive allocation to each community member according to each method (yearly evaluation).

Allocation method	Member (PV peak power)			
	1 (2 kWp)	2 (2 kWp)	3 (–)	4 (6 kWp)
#1 (novel performance-based)	25.78 %	24.74 %	23.10 %	26.38 %
#2 (equal)	25.00 %	25.00 %	25.00 %	25.00 %
#3 (proportional financial-based)	21.00 %	21.00 %	5.00 %	53.00 %
#4 (hybrid)	22.50 %	22.50 %	12.50 %	42.50 %
#5 (performance-based)	66.34 %	20.21 %	12.19 %	1.26 %

The combined use of the similarity factor (θ_m) and the utilization factor (η_m) in the proposed allocation method captures a complex balance between efficiency and equity in the redistribution of shared community incentives. The similarity factor θ_m rewards members whose consumption profiles closely follow the generation profile of the community. This aligns with traditional policy objectives that promote self-consumption, since users with similar generation and load profiles typically achieve higher levels of direct renewable energy use and contribute to grid stability.

In contrast, the utilization factor η_m introduces a targeted correction to prevent an unintended consequence of virtual energy sharing, where users with consistently high consumption profiles could benefit disproportionately simply by the amount of demand they generate. While self-consumption remains a parallel and desirable goal, η_m is designed to discourage the strategy of increasing energy use solely to absorb more shared energy and thus maximize incentives. It instead promotes a model where energy savings are valued alongside energy sharing. From this perspective, η_m acts as a safeguard that equalizes conditions within the community, ensuring that shared benefits are not weighted in favor of large (often non-residential) consumers with greater technical flexibility or infrastructure.

Taken together, θ_m and η_m offer a complementary mechanism: θ_m rewards behavioral and technical alignment with community generation (favoring users who naturally or intentionally synchronize load and generation), while η_m introduces a social and sustainability-oriented correction that values moderation and energy savings. This dual-factor approach reflects a broader rethinking of incentive structures within energy communities, balancing fairness, inclusivity, and environmental responsibility with technical performance.

5.4. Comparison of different allocation methods

While the advantages of the proposed allocation method have been extensively discussed in the previous sections, it is essential to establish a benchmark through comparison with other commonly used allocation strategies. This comparative analysis provides context for the proposed method and to highlights its potential benefits in real-world energy community scenarios.

Table 5 summarizes the annual percentage incentive allocation assigned to each member of the case study when applying the five methods introduced in Section 4.1. The analysis considers a full year of simulation to capture the temporal dynamics relevant to performance-based methods (#1 and #5), in contrast to the static nature of equal and proportional approaches (#2, #3, and #4).

Declaring one method to be definitively "fairer" than another is a challenging and complex task that depends on complicated relationships between energy, economic, and social dimensions. However, several critical insights emerge from the numerical comparison.

- Static methods (equal and proportional sharing) fail to reflect the dynamic and behavioral aspects of user participation in energy sharing. Their simplicity may come at the expense of incentivizing user engagement.
- Proportional methods, especially those based on financial input (#3 and partly #4), tend to disproportionately favor more financially capable members, reinforcing inequality within the community.
- Performance-based allocation methods that rely only on energy consumption (#5), do not account for the overall balance within the community. This can lead to highly unbalanced results, where users who consume the most energy receive the largest share of incentives, regardless of their contribution to the community. The strong imbalance shown in the results achieved by implementing method #5 clearly illustrates this issue.
- Methods with static designed allocation shares (#2, #3, and #4) offer administrative simplicity but provide limited motivation for users to actively participate or adapt their behavior in alignment with community goals, as promoted by EU directives on citizen-led initiatives.

The allocation method proposed in this paper seeks to bridge these gaps by encouraging proactive user behavior, while imposing internal safeguards to avoid over-rewarding major consumers or producers. This balance aims to preserve fairness in the allocation process while aligning with the European Union's vision of socially inclusive and participatory energy communities.

To further explore the concept mechanism of "fairness", possible extension of this work might try to incorporate need-based allocation method that are linked to users' socio-economic conditions. However, such an approach would require detailed data and assumptions that go beyond the current scope of this study.

6. Conclusions

After presenting the diverse context in which energy communities develop, consisting of challenges, opportunities, benefits and many limitations, this paper proposed a method for allocating an economic incentive based on the valuation of the energy virtually shared within an energy community. The allocation method presented is based on the assessment of two weighting factors. The first (θ_m) measures the similarity between production and consumption in the daily profiles of the community members. The second (η_m) evaluates the load utilization potential that could be covered by renewable production.

By means of a daily assessment carried out on an hourly basis, the dynamic allocation method is able to fit into any incentive scheme that values energy sharing between members of a community. The reward factors recognized by the proposed methodology relate to each member's ability to match their load/generation balance and to keep their consumption within the community's renewable generation potential. These aspects can be summarized in the concept of "energy virtuosity" of the members. Within this work, "energy virtuosity" is identified as the ability to synchronize the energy use with available renewable generation while minimizing overall consumption.

The allocation criterion was applied for a period of one year to a case study represented by a multi-family house consisting of 4 members gathered within the same community. Although the roles of the selected members were different, ranging from prosumers to pure consumers to mainly producers, the allocation method was able to distribute a hypothetical incentive, demonstrating flexibility during different periods of the year. In this case study, the proposed method generally rewards members who reduce their consumption in winter (through a higher utilization factor) and, in summer, those who synchronize their loads with the community's generation profile (via the similarity factor). This pattern is especially clear because the PV capacity in the community was designed to match its overall load. In general terms, the work's primary findings can be summarized as follows.

- The proposed allocation method rewards virtuous behaviors from an energy point of view, both in terms of the use of renewable resources and energy saving.
- The implemented method has demonstrated a strong component of fairness within the community, rewarding even members who do not have a renewable generation system, but who can still contribute to energy sharing through their contribution as exclusive consumers.
- In addition to a fair distribution from an economic point of view, the proposed method opens up many scenarios of member engagement with possible implementations from a social point of view, allowing members to increase their share of the incentive through virtuous behavior.

After testing its application, the proposed method was compared with four alternative traditional allocation schemes based on equal or proportional distributions. The results confirmed that the dynamic allocation method better reflects user behaviours and contributions to shared renewable usage. It demonstrated improved fairness in distributing incentives, particularly by recognizing both consumption timing and magnitude, as well as renewable production alignment. This comparative analysis provides further evidence of the method's ability to engage a broader range of community members and reward energy virtuosity more equitably.

For these reasons, this work claims that a strong allocation system must support an economic incentive system for the proper development and widespread diffusion of community-led energy initiatives. The allocation system should be able to satisfy the energy, economic and social aspects on which an energy community should be based.

An important limitation of the proposed method lies in the use of behind-the-meter energy flows, since it is based on each individual load and generation profile. This information is usually only accessible to individual members, not to a hypothetical community manager. More flexible allocation methods should only include the use of energy information from the POD, made available by the grid operator. This approach, however, would not be able to know the amount of energy self-consumed by the individual member, as it would be embedded in the import/export values measured on the POD.

6.1. Future perspectives

This work presents numerous possibilities for possible extensions. Future developments will certainly concern the application of the allocation method to a real-world case study, based on real-time monitoring of community energy flows. This implementation could facilitate numerous developments by leveraging Internet of Things (IoT) or hardware-in-the-loop technologies to encourage virtuous behavior (load profiles) among community members. In addition, the integration of such an incentive mechanism with energy forecasting tools could also support community engagement, optimizing its energy and economic benefits.

Another interesting research topic is certainly the study of the impact and role of energy storage systems under this incentive scheme. This technology, which is experiencing strong growth and development, was not considered in the proposed case study, but could be of interest in optimizing the energy consumption profile of the community.

While the proposed allocation scheme fits well within a policy-based incentive context, it is also worth acknowledging the potential of complementary models such as peer-to-peer (P2P) energy trading. These decentralized approaches can promote long-term, community-driven markets, offering greater autonomy from institutional incentives. However, P2P models face practical barriers, such as the need for clear regulation, robust infrastructure, and effective governance. These factors can limit their feasibility in less resourced settings, where policy-based frameworks such as the one proposed in this work provide a more practical entry point for emerging communities.

An interesting perspective for future development could involve a hybrid approach that combines the structured and accessible nature of policy-based incentives with the flexibility and market-driven potential of peer-to-peer (P2P) energy trading. This integration could support the evolution of energy communities toward greater resilience and autonomy by promoting better synergy between enabling technologies and regulatory frameworks.

Finally, from the point of view of social engagement, this work may open up future implementations of the allocation method within platforms for the management and involvement of users within an energy community, providing the basis for a fair and equitable allocation to all stakeholders involved in the market.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Matteo Bilardo reports financial support was provided by Government of Italy Ministry of University and Research. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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