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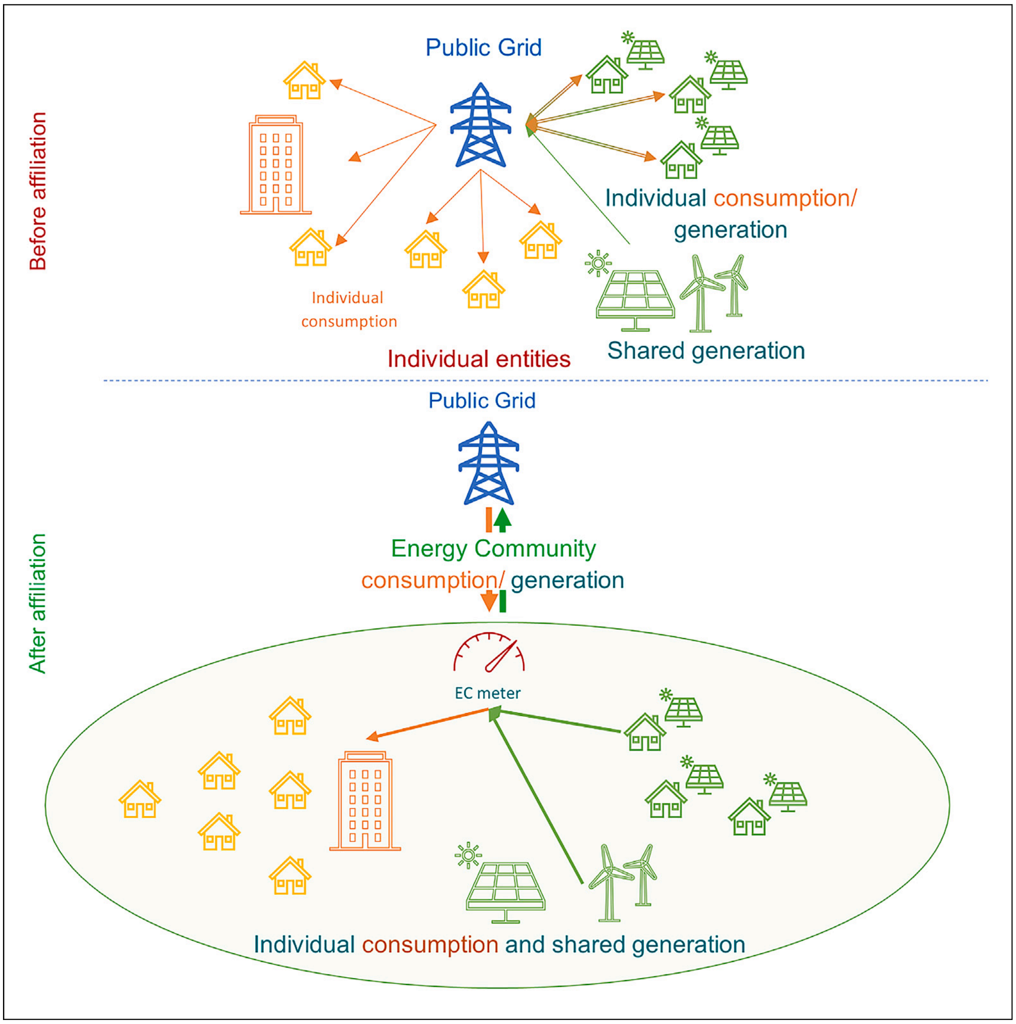


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## Highlights

Energy communities' stakeholders and archetypes

Maximizing the value of RES, minimizing the costs

Value sharing using load-generation profile and empowering local markets

Extracting benefits from value sharing flexibilities

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# A value sharing method for heterogeneous energy communities archetypes

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## SUMMARY

**A novel value sharing (VS) method is proposed that distributes the energy communities (ECs) value based on the individual contribution to the total surplus/deficit. It considers the *load-generation profile* of each EC member and allocates a higher share to members who contribute to the EC revenue. The lowest share is received by the members with the highest demand that has to be supplied from the shared generation or from the grid, contributing to the EC cost. Several allocation methods are compared using the fairness index (FI), and, for setting the strategy of the EC using a decision model, as the strategy may vary over time, an objective function is defined as a combination between FI and self-sufficiency index using weighting coefficients. The methodology is implemented as an algorithm that automatically calculates and distributes the gain. For the proposed VS method, the FI is between 0.81 and 1.**

## INTRODUCTION

The Clean Energy Package (CEP) emphasized the citizens' initiatives[1] in the Directive (EU) 2019/944 of the European Parliament and the Council of 5 June 2019 on common rules for the internal electricity market electricity (IEM Directive)[2] and Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable energy sources (RES Directive)[3] that can be organized into energy community (EC) and benefit from a regulatory framework.[4,5] Defining the EC in the CEP led to their creation, recognized them as a new actor and potential market player, and provided stimulus to locally generate electricity based on RES.[6] As the EC members are various (i.e., residential consumers or households, prosumers, buildings of apartments with rooftop photovoltaic (PV) systems, public buildings and other facilities such as schools, hospitals, administrative buildings, swimming pools, etc., storage units, and generating units), numerous models can be envisioned to operate these ECs and ensure their growth. For instance, several approaches regarding the integration of more PV system at the consumer level, the involvement of consumers in the generating and trading activities, and the way they are stimulated have been conceived differently at the national level. The EU regulation left the decision makers with the ability to tailor solutions according to the potential and particularities of each country.[7] As a result, the green EC projects and living labs have emerged in various forms of flexibility[8]: 1) as storage projects, e.g., Better Energy and Hybrid Greentech; 2) aggregating business, e.g., Neas; 3) electric vehicle (EV) charging stations, e.g., Nuuve and Clever; and 4) home energy systems, e.g., EnergyLab Nordhaven.

In the Nordic countries, resilient progress has occurred as they have a long tradition in this field. All consumers in Copenhagen benefit from smart meters and dynamic tariffs. They are able to trade energy on Nord Pool. The Nordic countries are probably the most advanced countries in the creation and growth of the EC.[9] Their first initiative started as RES cooperatives in 1996, when Middlegrunden, probably the first wind-based cooperative in Europe, was established.[10] Today, the EC involvement in local generation using RES is well sustained by several stimuli such as green scheme, guarantee fund, option to purchase, and value loss. The option-to-purchase agreement allows citizens and their initiatives to purchase shares of the RES-project investment. The Dutch government issued specific legislation to sustain decentralized generation of RES in 2015. Several microgrids and citizen communities have emerged.[11] Next Kraftwerke is active in numerous European countries (Netherlands, Belgium, Germany, Austria, Poland, France, etc.) and acts as a virtual power plant (VPP),[12] aggregating small, decentralized generating units, prosumers, and consumers to provide flexibility to the power system.[13]

The UK and Poland focused more on testing various business models and experiments. Associations such as SmartKlub and OVO have promoted peer-to-peer (P2P) trading and novel tariff systems, settlement, and payment methods.[14,15] Furthermore, Freiburg and Bristol are two successful projects that support new approaches in the local trading field.[16] Also, in Poland, the government promoted experiments. The energy cluster concept was invented in 2016 to conceive new rules and experiments for successful operation of the cluster as a community. As a result, the Gliwice district Energy Cluster[17] and the Baligród Renewable Energy Micro Cluster emerged from these experiments.[18] On the other hand, Demark and Germany were more conservative and provided incentives to local trade at the EC level.[19]

Furthermore, in Italy, a new regulatory framework was released in 2020 to support consumers and prosumers to benefit from local sources and trade. Feed-in premium is given to the consumers if they consume from own generation, and, if they share energy, more deductions and

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incentives are provided per MWh.[20] An electricity triangle for energy transition with implementation in Italy was proposed.[21] In the meantime, numerous RES projects and campuses (e.g., Savona) have been transformed into veritable EC.

In Romania, funds were provided to install PV systems up to 3 kW per consumer. This capacity can hardly cover single families' requirements during summer. The 1:1 kWh generation/consumption compensation is nowadays promoted, but the system is like a huge battery for prosumers losing interest in load optimization on the consumption side. Various compensation schemes are tested. However, the strategy makers discuss other supporting regulations regarding the offsetting of generation and consumption at different locations of the same owner. Unfortunately, delays in offering grants, funding the projects, and installing the smart meters at prosumers' location still hinder the PV systems penetration at the power system level. A vision of the Romania's path to sustainable development was provided by Ciucu-Durnoi et al.[22] using a prognostic approach. The researchers predicted the path of some of the sustainable development goals regarding agriculture, energy poverty, pollution, innovation, sharing principles, banking systems,[23] youth education, etc., values that were predicted for medium and long term using Autoregressive Integrated Moving Average (ARIMA) and a historical dataset that spanned from 2015 to 2021.

In this paper, we investigate the potential of the existing value sharing (VS) methods and propose a novel and more efficient method. We are motivated by the large number of consumers in the urban cities that may benefit from PV systems. As of now, the governmental policies are targeting individual households, offering grants to install PV, but the residential buildings with more apartments will be the next target. They will be empowered with PV systems and will be in need of sharing the value generated by the emerging community. We refer to "value share" in ECs as payment or revenue shares also considering the ownership quotas. The value share is closely related to the benefits of joining the EC. Therefore, the importance of its proper sharing is tremendous as the newly created ECs are perceived based on the principles behind the value share method applied at the EC level. Additionally, the value share is reflected by the participation in an EC and its benefits are formulated as the difference between the total payment/revenue amount of the EC and the amount of individual payments/revenues. Furthermore, we are motivated to examine the VS methods by identifying the drawbacks of the existing methods.

Sharing the benefits or advantages among the EC's members ensures the development and the spread of the EC. These can be a) savings from cost reduction or revenue from selling the surplus of energy, b) self-consumption or self-sufficiency, c) reduction of $CO_2$ emissions, and d) appurtenance to EC membership improving the social interaction at the EC level and alleviating the energy poverty.[24] Some benefits, such as c) and d) are not always easy to assess,[25] whereas a) is complex as benefits can be allocated in various modes: equally to the number of members, to the consumption level, and according to marginal contribution or an average marginal contribution of all subgroups known as the Shapley value method.[26,27] An additional way is to consider topological constraints such as electrical distances. An applicable approach can be found in Cuenca et al.[28] Another study proposed three value sharing mechanisms: a) financing services sharing the benefits according to the ownership share of the generation assets, b) self-consumption services sharing the benefits according to the contribution to self-consumption of the energy locally generated, and c) both financing and self-consumption services.[29] The results of this study indicated that the mechanism would favor the investors, self-consumers, or vulnerable consumers. The authors stated that "choosing the right sharing mechanism is therefore a matter of determining *a priori* and within the EC what a fair mechanism is."

Nonetheless, there are cases when the investment is not shared by the consumers; therefore, the financing service sharing mechanism is not applicable. When the investment is shared, Safdarian et al.[30] proposed a coalitional game theory-based value sharing in EC and demonstrated that the Shapley value does not ensure the stability of the community. In this case, the size of the optimization problem increases exponentially with the size of the EC as the number of possible combinations is particularly large. The authors proposed to cluster the EC using K-Means in terms of profiles and reduce the dimensionality. Thus, the share is performed at the cluster level. Furthermore, game theory was applied by Gjorgievski et al.[31], who proposed a sharing method that addressed collective self-consumption by providing a fair energy sharing method based on the members' individual contribution. A mathematical model was proposed and explored using a cooperative game theory approach. 600 hypothetical ECs generated based on real data were created to perform simulations. Additionally, the authors proposed an assessment framework that used 3 indicators for comparison with other energy sharing methods, proving that the proposed method offers the best balance between computational complexity and fairness.

Lin et al.[32] investigated an optimal sharing energy of a complex of houses through energy trading in the Internet of Energy[32] aiming to speed up the RES usage and decrease the stress of overloading the electrical grids. The authors proposed a mixed-integer programming model for the optimal energy sharing to the residential consumers using a market platform so that the total profit of the residential consumers is maximized. The results showed that the proposed solution brought significant savings and peak shaving. The average profit of a residential consumer can be around 70 cents per day. Moreover, self-consumption for the EC in Spain was analyzed under the new legal framework.[33] Other energy sharing mechanisms and customers' options were proposed assessing P2P energy sharing mechanisms based on a multiagent simulation framework.[34,35] However, energy sharing methods are various[36,37] in the literature, and their goal is different from VS mechanisms that refer more to the monetary aspects of sharing the benefits and costs.

Buying and installing facilities that are used in common can play a very significant role in developing the EC and making it a regular landscape in the European countries and beyond. The results indicated that the optimal sizing of the generating devices brought valuable savings to self-consumers regardless of remuneration level for surplus. The study revealed that storage facilities were not yet cost-effective. In addition, energy compensation mechanisms made batteries even less cost-efficient, especially when the cost of PV systems became lower. However, feeding the PV surplus into the grid proved less efficient, and an energy surplus remuneration was required.

Other studies focused on comparing VS methods for different types of EC and adjusted marginal contribution or Shapley methods.[38,39] An optimal allocation method for a fair distribution of the benefits in an EC is proposed by Casalicchio et al.[40] The authors emphasized the marginal contribution VS method, fairness of the approach proposing a fairness index (FI, Gini), and several business models (BMs) to create

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simpler VS methods not involving optimization. These BMs are defined as 1) homogeneous distribution including investment, 2) excluding investments, 3) sharing according to the consumption, 4) per capita, and 5) sharing considering self-consumption. Autonomous ECs based on energy contracts are presented by Wang et al.[41] They rely on autonomous home energy management (HEM) and a P2P energy sharing mechanism,[42] proposing an autonomous EC model using energy contracts.

The Shapley value method is widely used in numerous fields[43] as a competitive resources sharing method. For instance, Cremers et al.[44] focused on the Shapley value method that demonstrates its computational complexity. They proved that for small- to medium-size EC the method can be implemented, but, for larger communities with several hundred members, they proposed a new method based on the stratified expected value approximation that efficiently approximates the Shapley value using two large datasets from the UK. For large ECs, they proposed clustering members into a smaller number of load profiles that simplify the implementation of the method. Furthermore, an adaptive method of Shapley value for compensating participants in DR programs is proposed by O'Brien et al.[45] They implemented reinforcement learning techniques to provide an adaptive sampling to calculate the Shapley value. Similar results were obtained with both methods according to Cremers et al.[44] Furthermore, estimations of the Shapley value of a P2P energy sharing game using multi-step coalitional stratified and random sampling were provided.[46,47] The authors combined rewards and coalitions from game theory with principles of Shapley value method to fairly distribute the benefits at the EC level.

Several efficient methods for approximating the Shapley value for sharing the assets in EC were proposed by Cremers et al.[48] as the aspects of fair distribution of benefits and costs have become increasingly significant in order to develop the EC ecosystems. As the Shapley value allocation method becomes computationally complex beyond a few dozen users, the authors investigated several methods to approximate the Shapley value. They clustered consumers based on their load profile and performed simulations with an EC of around 200 households located in the UK. The approximation proved to be feasible providing similar results in terms of efficiency but at much lower computational effort. Moreover, an electricity cost sharing in EC under dynamic pricing and uncertainty was proposed,[49] as a post-process sharing method that relies on a 2-stage mechanism which provides benefits for prosumers joining the EC and supports the EC growth.

Numerous studies have noted that the fairness of value sharing and the stability of EC are highly correlated.[50,51] Stability is important as the EC may grow and become a good practice for other emerging communities. This idea is also strengthened by the fact that not all ECs were successful.[52] In the US, the program Green Tariff Shared Renewables showed low enrollment as consumers lost interest in it. The consumption correlation with the availability of the PV output may solve the VS problem, as, in a building with numerous consumption profiles, it may not be fair to share the benefits equally among consumers that consume when PV output is available and those that consume in the evening or at night when the PV output is no longer available.[53] Both the marginal and Shapley value allocation methods are better than equal or pro rata per volume/capacity allocation because they split according to the real value generated by each member.[54] Therefore, the consumer who consumes when PV generation is available brings more value and should obtain more. The stability of the community is given by the assessment of each consumer/prosumer. If he/she is better without community, the stability is lost, as he/she will exit the community. The same rules apply to a group of consumers/prosumers within the community. If they as a subgroup would have been better outside the EC, they would leave the EC and create their own community.[55] Usually, the sharing process is based on input data from smart meters and can be performed automatically, implementing the rules as procedures that ensure the stability of EC (such as marginal contribution rule), performing computation in several seconds. These principles of value sharing are particularly significant in the EC and in energy building management of blocks of apartments that has to consider various load profiles and a common investment in RES assets and/or storage facilities.[56] EC shared-generating assets require VS mechanisms and related services to allocate the benefits and sometimes costs to the EC members. Therefore, a very common use case can be a multi-flat block building with PV systems on top or a small- to middle-size community of several houses with shared PV systems that are not only located on the roof.[57] These communities may have members who invested in the generating/storage assets with equal investment quota (type-A) or individual (not equal investment quota)—type-B—or they did not contribute with capital in the generating assets—type-C (PVs were donated or a grant was offered).[58]

According to the previous studies, VS methods are various, based on a) the number of households, b) per capita, c) the consumption level, d) the PV quota or share, e) marginal contribution to EC gain, and f) direct and indirect contribution to total revenue and cost.[59] Nonetheless, the scope of the value sharing is multiple[60–62] as discussed below.

- Fair and keep the existing coalition in the EC: a value sharing method has to ensure the EC stability, development, and growth. Therefore, all members have to be satisfied or to be better inside than outside the EC.
- Transparent. Details have to be provided to the EC and any other party interested in the value sharing mechanism. By implementing a transparent VS method, there is a good chance to extend the EC or to replicate the method to other buildings, for instance.
- Flexible. The mechanism must be open to changes, as the shared assets' lifetime spans 20–25 years and a better solution can be envisioned anytime. If the mechanism is changed due to technological progress, then the differences between old and new mechanisms have to be evident, and the advantages of the new one have to be known by the existing or potential members.
- Adequate. There is no unique or perfect solution for all ECs. The mechanism has to respond to the following questions: *What are the needs of the heterogeneous EC? What are the existing programs in the local area? What are the concerns of the members related to the value share allocation? How to gain independence from the main grid?*

After analyzing the existing allocation methods, many of them provided as approximations of Shapley value method or related to the energy sharing principles and less to the value sharing in terms of financial benefits and costs, we identified that none of the previous methods focused on individual contribution of members to the total surplus or deficit. This leads us to notice a significant research gap. The novelty of our proposal consists of integrating the *load-generation profile* of each EC member and allocating a higher share to members who contribute to the EC revenue, whereas the lowest share is received by the members with the highest demand that needs to be covered from the shared generation or from the grid, contributing to the EC cost. Furthermore, as an original contribution, the proposed methodology is implemented as an algorithm (a decision model) that automatically calculates and distributes the gain. The methodology is evaluated in three types of EC to assess the results. However, the objectives of an EC may vary over time. Early in its existence, a goal of the EC may be to grow and attract more members using a light VS implementation, while later, when members are stable and understand different approaches, a more complex VS can be applied. Therefore, when setting the strategy of a mature EC, the proposed VS method is automatically selected by the algorithm to maximize the objective function.

The main contribution of this paper and its innovative points consist of the following.

- Proposing a methodology for establishing the strategy of the EC using a decision model based on an objective function that maximizes the combination of the fairness index (FI) related to the value share allocation and the independence degree expressed by the self-sufficiency index (SSI).
- Proposing a VS method that is based on the load-generation profile of each member. Members who have moderate consumption (load) and generation surplus are rewarded more. This is in line with the EC development and growth concepts.[63,64]

As derived from the two aforementioned contributions, in this paper an assessment of several value sharing methods using several metrics, such as FI, self-consumption index (SCI), SSI, and cost savings is performed. Comparison of the methods reveals interesting insights that are presented in the results and discussion sections. Our method proved to bring more benefits to heterogeneous EC that are more prevalent. Moreover, in this paper, we implement the proposed method using an algorithm that automatically calculates the payments and gain of the EC, allocates the value share to its members using several methods, calculates the metrics (cost savings, SCI, SSI, and FI), and determines the optimal method that maximizes the objective function corresponding to the strategy of the EC. Thus, the algorithm represents a decision support model for setting up the EC strategy, as it may vary over time. For instance, early in its existence, the EC may be focused on growth; after that, it can be more focused on gaining more independence and resilience.

The proposed methodology is applied on three EC archetypes. The metrics are calculated, and the optimal model for each community is selected using the proposed algorithm. Useful insights are revealed and discussed in each case. Additionally, in order to analyze the effect of load optimization on the value share allocation, in the results section, we consider a scenario where a load optimization model is applied to shift the consumption from the peak to the hours with available generation. The results reveal that the individual gains are increasing; thus, all members benefit from the load optimization. To the best of our knowledge, we combine for the first time the concept of value sharing and load optimization showing the benefits of such a combination.

## RESULTS

In order to evaluate the proposed methodology and compare the VS methods, the simulations are performed on three scenarios corresponding to three types of EC architectures, which are listed in the following.

- EC1—a small community with 11 houses that share a PV system with 50 kW installed power. The generation quota is equally distributed among the members. Moreover, most of the houses have their own generation/PV systems with various capacities, and the surplus of the generation is shared among the other members of the EC: 3 houses have smaller PV systems (up to 3 kW) and 4 houses have PV systems with higher capacity (between 8 and 10 kW).
- EC2—an urban community that consists of a building with 114 apartments that have installed a PV system of 50 kW on top of the building. Each member has the same shared quota of the PV system.
- EC3—a larger community composed of the two previous communities: 11 houses and the building with 114 apartments that share a PV system with 50 kW installed power.

The datasets are downloaded from UMass Trace Repository.[70] The same 15-min time resolution is used for the datasets. Therefore, they are merged, and a final dataset is obtained, corresponding to one-year records between 1st of January 2021 and 31st of December 2021. For each type of community, we analyzed the allocation in the winter and summer seasons, since the load profile and generation vary significantly and influence the EC value share and distribution.

The members of these communities are grouped into three profiles corresponding to the load and generation curves, which are listed in the following.

- LP1—low consumption and high generation that leads to a surplus used in the community or injected into the grid for which the member receives revenue. The members with this profile usually have a very small cost during the winter and receive considerable revenue during the summer.
- LP2—moderate consumption with a small generation surplus during the day. The members in this category have a moderate cost during the winter and a small cost during the summer.
- LP3—high consumption with insufficient generation to cover the demand. The deficit needs to be supplied by other members that have surplus or are imported from the grid. These members have a high cost, especially in the winter.

**Table 1. Evaluation metrics for winter and summer seasons for three EC archetypes**

| Season | Community | CS | SSI | SCI | FI EQ | FI G-based | FI C-based | FI MC | FI Shapley | FI CG |
|---|---|---|---|---|---|---|---|---|---|---|
| Winter month | EC1 | 13% | 0.38 | 1 | 0.79 | 0.77 | 0.28 | 0.79 | 0.79 | 0.81 |
| | EC2 | 2% | 0.02 | 1 | 1 | 1 | 0.91 | 1 | 1 | 1 |
| | EC3 | 4% | 0.05 | 1 | 0.95 | 0.90 | 0.80 | 0.95 | 0.95 | 0.97 |
| Summer month | EC1 | 68% | 1 | 0.8 | 0.79 | 0.75 | 0.49 | 0.74 | 0.73 | 0.83 |
| | EC2 | 20% | 0.2 | 1 | 1 | 1 | 0.95 | 1 | 1 | 1 |
| | EC3 | 26% | 0.34 | 1 | 0.96 | 0.93 | 0.88 | 0.95 | 0.95 | 0.98 |

The distribution of these profiles depends on the community structure. Thus, for EC1, around 36% of the members are in LP1 having high capacity from their own generation sources, 36% are in LP2 with moderate consumption and small generation, and 28% in LP3 with high consumption and without or with very small generation sources. For EC2, since the members do not own individual generation sources, only 5% of the members are in LP1 having a low consumption almost covered by their quota from the shared generation, 80% in LP2 having a moderate consumption, and 15% in LP3 with high consumption. For EC3, 9% of the members are in LP1, 15% in LP1, 75% in LP2, and 16% in LP3.

The members can switch from one load profile to another due to their dynamic consumption behavior. They may change their consumption pattern from winter to summer due to seasonal necessities or because of other exogenous variables that are not captured by the datasets (e.g., occupancy, retrofitting the electric appliances, house insulation, change on the income). Thus, in winter, some of the members have electric heating that leads to an intensive consumption all day long, while in summer they may use electric cooling for shorter periods, thus decreasing the consumption compared to the winter season.

The costs and revenues are calculated using the same rates for all communities: time of use (ToU) = 0.8 Euro/kWh at peak, ToU = 0.5 Euro/kWh at peak, and feed-in tariff (FIT) = 0.3 Euro/kWh.

The proposed CG method is compared with the other 5 methods: 1) equal quota (EQ), 2) generation-based (or G-based), 3) consumption-based (C-based), 4) marginal contribution (MC), and 5) Shapley allocation. The comparison is done in a qualitative manner following six criteria: 1) tariff rates influence the individual quota, 2) adequate, 3) stimulate peak shaving, 4) computational complexity, 5) fairness, and 6) transparency and understandability. Based on this initial comparison and identifying the main characteristics or specificity of each method, for the quantitative comparison, we implemented the proposed algorithm and tested it for the two seasons (winter and summer). The numerical comparison is provided in Tables 1 and 2. Moreover, a graphical comparison is provided in Figures 4, 5, 8, 9, and 10.

## Value share in the winter season

Although the communities have installed PV power plants with high capacity, the weather conditions in the winter season have a negative influence on the generation and usually the generated power is not sufficient to cover the total load. Therefore, the communities are mainly supplied by the grid. In Figure 1, the load profile and the generation from own and shared sources are shown for community EC1, which has the highest generation power.

The SSI is around 0.38 for EC1, and the generated power is consumed locally; thus, the community needs to cover the demand from the grid. The cost savings of the community are 13% compared to the non-affiliation case, and the total gain is 95.7 Euro. The share of the gain depends on the members' profile and the allocation method: EQ method distributes a fixed amount to each member, G-based and C-based methods consider only the generation and consumption quotas, respectively, the MC method distributes the value using Equation 14, Shapley is very similar with MC and the gain is allocated using Equation 15, and the proposed CG method allocates the gain based on the individual contribution to the deficit (consumption) or surplus (generation) using Equation 19. The distribution is presented in Figure 2 for each type of load profile (own and shared generation are stacked).

The EQ method allocates a fixed amount of 8.7 Euro to each member. The G-based method allocates the largest amount to members with profile LP1, while C-based rewards the members from LP3 with the highest gain. The MC and Shapley methods provide similar results,

**Table 2. Strategies of the three EC archetypes**

| Season | Community | $\alpha$ | $\beta$ | $\delta_{EQ}$ | $\delta_{CG}$ | $\delta_{MC}$ | $f_{EC}(EQ)$ | $f_{EC}(CG)$ | $f_{EC}(MC)$ |
|---|---|---|---|---|---|---|---|---|---|
| Winter month | EC1 | 0.8 | 0.5 | 0 | 0.7 | 0.5 | 0.82 | **0.97** | 0.92 |
| | EC2 | 0.5 | 0.8 | 0 | 0.7 | 0.5 | 0.52 | **0.53** | 0.52 |
| | EC3 | 0.65 | 0.65 | 0 | 0.7 | 0.5 | 0.65 | **0.69** | 0.67 |
| Summer month | EC1 | 0.8 | 0.5 | 0 | 0.7 | 0.5 | 1.13 | **1.51** | 1.34 |
| | EC2 | 0.5 | 0.8 | 0 | 0.7 | 0.5 | 0.66 | **0.77** | 0.74 |
| | EC3 | 0.65 | 0.65 | 0 | 0.7 | 0.5 | 0.85 | **1.01** | 0.95 |

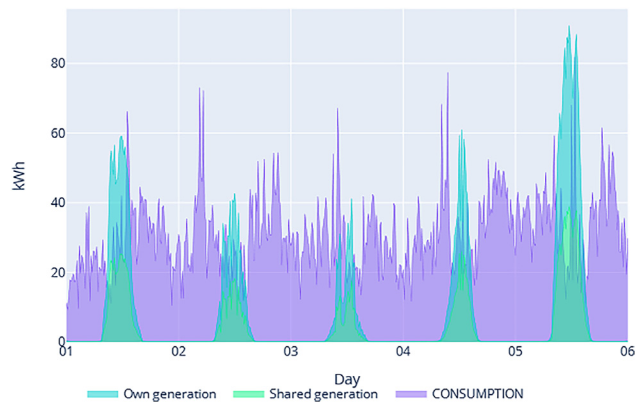


**Figure 1. EC1 load profile and generation between 1st and 5th of January 2021**
The shared and own generation and consumption are represented for EC1.

allocating less than EQ for LP1 members, similar to EQ for LP2, and a higher gain to LP3. The CG method allocates a higher share of the EC value to the members with a higher contribution to the surplus (LP1) and a lower share to the members with high consumption and high deficit (LP3). Thus, the method penalizes high consumption, encourages local generation, and stimulates the local share of the surplus that compensates the deficit caused by the members with a high demand.

For members with moderate consumption and generation (load profile LP2), the differences between the allocation methods are smaller. Therefore, in the case of communities with numerous members with the LP2 profile, any of the methods can be applied.

The differences between the share allocated by CG and the other methods to each member in EC1 are depicted in Figure 3. Members in LP1 (M4, M5, M6, M11) that have high generation quotas receive the greatest gains with G-based, but also with CG method. The difference is that CG allocates less share than G-based, distributing the value share of the community in a moderate way. The MC and Shapley methods allocate the greatest share to M6 and M11, more than CG, but for M4 and M5 the share is less than CG. This can be due to the tariff rates and the contribution of these members to the total payment. These aspects are discussed at the end of results section. For members in LP3 (e.g., M7), the CG method allocates the smallest amount, followed by Shapley and MC, while the C-based method allocates the greatest share (40.3%). Therefore, for the G-based and C-based, the shares of the LP1 and LP3, respectively, are extremely high compared to the other members.

Using the CG method, the lowest gain (2.9%) is received by M7 which has the highest consumption (9 kWh off-peak and 16 kWh on-peak) without having its own generation sources. MC and Shapley methods penalize M4 and M5 which have a major contribution to the surplus, sharing their own generation (up to 15 kWh) and covering the demand of the other members. On the other hand, the CG method rewards these members that compensate the community deficit and rewards them with high gains (9.9% and 11.5%). Thus, the CG method stimulates the members that contribute to the surplus and helps EC to increase its independence from the main grid. The members from LP1 profile gain more with CG compared to EQ, MC, and Shapley, while the members from LP3 profile gain less with CG compared to these methods. Therefore, the CG method can be applied in case the strategy of the community is to increase its independence from the grid, since it rewards the members with higher contribution to the surplus and penalizes the members with high consumption.

Furthermore, to compare the proposed method with the existing ones, the allocation methods are applied to the other two communities, EC2 and EC3, and similar findings are obtained. These two communities (EC2 and EC3) have a larger gap between the local generation and load, especially in the winter (Figure 4).

Thus, due to a low generation in winter, for EC2, the total gain is 146 Euro and for EC3 it is of 242 Euro. The individual gains are significantly reduced compared to EC1. For example, in January, the EQ method allocates 1.2 Euro to each member of the EC2 and 2 Euro to each member of the EC3. MC and Shapley methods allocate similar gains to EQ with small variations (– 0.07 for LP1 and +0.05 for LP3). The proposed CG method allocates more to LP1 members (around 1.3 Euro for EC2 and 2.2 Euro for EC3) and less to LP3 members (around 1.1 Euro for EC2 and 1.8 Euro for EC3). Therefore, the hypothesis that CG favors the surplus contributors is also demonstrated for EC2 and EC3.

## Value share in the summer season

During the summer, on sunny days with low demand, the total generation exceeds the consumption (as in Figure 5) in the middle of the day—at noon, and the community injects the surplus into the grid, receiving revenue. In the case of EC1, the SSI is 1 and the SCI is 0.8; thus, a considerable amount of surplus is injected into the grid.

The cost savings of the EC1 compared to the non-affiliation case in July is 68%, and the total gain is 160.6 Euro. Using the EQ method, the gain is distributed equally between the members, each of them receiving 14.6 Euro. The same differences observed in the winter season are obtained in the summer using the methods depending on the load profile of the members. Thus, the CG increases the gain of the members with high surplus and decreases the gain of the members with high demand (as in Figure 6). Since the EC1 receives revenue by selling the total


**Figure 2. Value share in January 2021 for each load profile in EC1**

The load profiles for LP1, LP2, and LP3 are represented in the left column, while the distribution of the value share is represented in the right column using the following methods: equal quota (EQ), the proposed method (CG), marginal contribution (MC), consumption generation-based (or G-based), consumption-based (C-based), and Shapley.

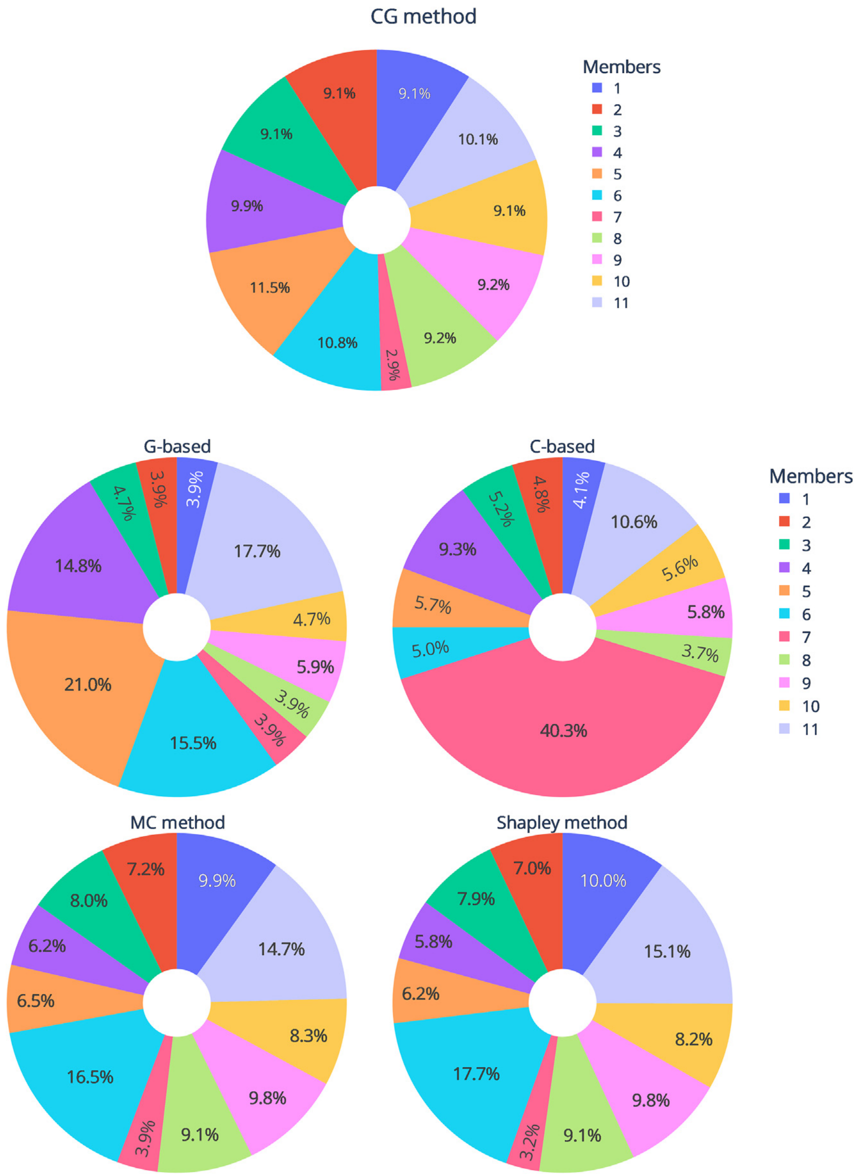


**Figure 3. Comparison between the gain distribution obtained by CG and the other methods for EC1 members in January 2021**

The gain obtained by applying the proposed method (CG) is compared with the gain obtained with following methods: consumption generation-based (or G-based), consumption-based (C-based), marginal contribution (MC), and Shapley.

surplus to the grid, the gain of the LP1 members varies between 15 and 18 Euro, while for members with LP3 the gain varies between 9 and 12 Euro. Members with LP2 receive around 15 Euro with CG, MC, and Shapley methods, similar to the gain allocated by EQ method. The same extreme allocation pattern is observed in the case of the G-based and C-based methods that reward the members with high generation and high consumption, respectively.

An interesting finding is observed in the case of two members of the EC1 community. In winter, M7 had the highest hourly consumption (between 9 kWh during off-peak and 17 kWh at peak), while in the summer he changed his behavior and decreased the consumption to 1.5 kWh during off-peak and 5 kWh at peak. Although he remains in the LP3 profile, the shared-value quota increases from 2.9% in January to 7.1% in July with the CG method (as in Figure 7). Therefore, the proposed method is sensitive to the changes in the consumers' behavior.

A significant change in the load profile is observed in member M8. In winter, he belonged to the LP2 profile, having a moderate consumption (between 1 and 3 kWh) and received 9.2% of the gain with CG and 9.1% with MC and Shapley. In summer, he increased his consumption (between 2 kWh during off-peak and 7 kWh at peak), switching to the LP3 profile. Therefore, the C-based method allocates the greatest gain to M8 (21.1%). CG allocates only 5.7% of the EC1 value, while MC and Shapley allocate 10.8% since its contribution to the community payment

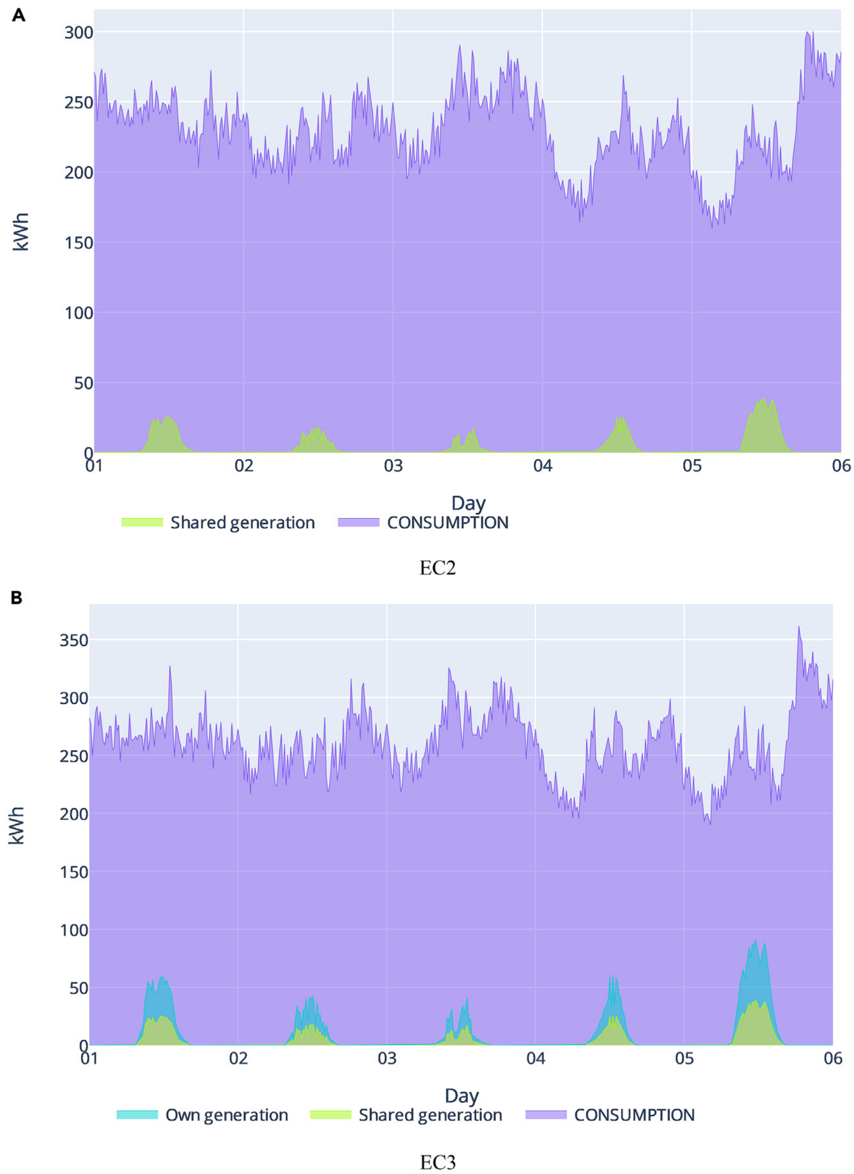


**Figure 4. EC2 and EC3 load profile and generation between 1st and 5th of January 2021**

Shared and own generation and consumption are represented for EC2 (A) and EC3 (B).

increases. M8 receives a lower percentage than M7 with the CG method, as M8 has the highest demand in the community and its contribution to the total demand is the greatest. Thus, the hypothesis that the proposed method CG is sensitive to the LP is confirmed. Moreover, the proposed method CG encourages higher generation/lower consumption at the local level.

Compared to EC1, for EC2 and EC3 the generation is insufficient to cover the demand, not even in the summer season, so the deficit is still covered by the grid (as in Figure 8).

Both communities take advantage of the affiliation; the total gain in July for EC2 is 332.8 Euro and the total gain for EC3 is 532.5 Euro. The EQ method allocates 2.9 Euro to each member of the EC2 and 4.3 Euro to each member of the EC3. The MC and Shapley methods have small variations compared to EQ for both communities (−0.3 Euro for LP1 and +0.6 Euro for LP3). The proposed CG method allocates for EC2 around 3.2 Euro for LP1 and 2.6 for LP3, while for EC3 it allocates around 5.3 Euro for LP1 and 3.4 for LP3.

Analyzing the differences between the CG, MC, and Shapley methods, for both seasons, one can notice that the CG method is sensitive to the load profile and consumption behavior, while the MC and Shapley methods are more influenced by the payment contribution that depends on the tariff rates. The CG method encourages load reduction and surplus contribution (including more investment in PV systems), while the MC and Shapley methods consider the contribution to the community payment that is related to other members' consumption and monetary aspects. Thus, if the FIT is very low compared to the ToU tariff rate (in our case, FIT is 50% of ToU), then the marginal contribution

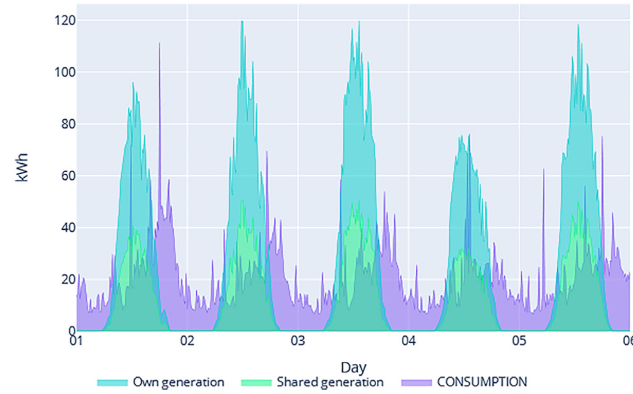


**Figure 5. EC1 load profile and generation between 1st and 5th of July 2021**

The shared and own generation and consumption are represented for EC1.

of the members with surplus will be lower than that of members with high consumption since the difference between the EC value share with and without these members will be lower (according to Equation 13). On the other hand, the CG method is not influenced by the tariff rates and considers only the individual contribution to the community surplus or deficit (as in Equation 19).

Regarding the evaluation metrics for the communities obtained for winter and summer seasons, these metrics are centralized in Table 1.

The FI depends on the allocation method and the structure of the community. Thus, for a homogeneous community such as EC2 in which all members have the same share of generation, the FI is equal to 1 for most methods (except C-based). In this case, the CG, MC, and Shapley methods allocate similar gains to the members, while G-based and C-based have higher fluctuations. For communities with heterogeneous structure such as EC1 in which there are members with their own generation sources, the FI varies from 0.28 for C-based to 0.81 for CG. Thus, a higher value of the CG method indicates a better allocation method that stimulates members with a significant contribution to the local generation that covers the demand of other members and compensates for the deficit of the community.

## Load shifting influence over the allocation methods

From Figure 5, it can be noticed that the total consumption in the summer season varies between 10 kWh during off-peak (from 00:00 a.m. to 10:00 a.m.) and 45 kWh at peak (from 02:00 p.m. and 11:00 p.m.) having some spikes in the morning around 7:00 a.m. The generation curves have a typical solar generation distribution, with a maximum between 11:00 a.m. and 03:00 p.m. So, the generation peak and the load peak do not overlap. There is a large amount of PV generation around 11:00 a.m. that is injected into the grid and can be used locally if a load optimization is implemented in the community. Several optimization methods for the communities have already been proposed before,[71–73] and their benefits are evaluated and demonstrated by extensive simulations.

In this section, we evaluate the influence of the load shifting over the allocation method by using the optimization model proposed by Oprea et al.[74,75] The optimization model aims to maximize the consumption from self-generation if available and minimize the electricity cost for consumers. Four algorithms for modeling the optimization function are proposed by Oprea et al.[74]: i) minimizing the amplitude of the daily consumption vector, ii) maximizing the minimum consumption, iii) minimizing the maximum consumption, and iv) dispersion minimization algorithm. The algorithms run in parallel at the level of the community, and the best option is selected for day-ahead optimization. It is defined by the community as maximizing the consumption from own sources or minimizing the electricity payment. Oprea et al.[75] enhanced these optimization algorithms by a Stackelberg-type dynamic non-zero-sum game. The algorithms run on the edge nodes (consumers' houses or devices), and the optimized individual schedules are sent to the community administrator or retailer. The individual schedules are aggregated, and the retailer/EC administrator adjusts the tariff rates and sends a new signal to the consumers to re-optimize the consumption. The game continues until the community savings and the flattening index are maximized. The flattening index is calculated as the ratio between the average consumption and the consumption at peak. These models are implemented in the current paper to determine the day-ahead optimal schedule. To consistently evaluate the results using the same ToU and FIT as in results section, only one iteration is performed to optimally schedule the day-ahead consumption.

Thus, by shifting the consumption from hours with low generation to hours with surplus (as in Figure 9), the cost savings of the community EC1 increase from 68% to 80%, having a total amount of 191 Euro in July.

The EQ methods distribute an equal amount of 17.72 Euro to each member. The CG method allocates between 19 and 21 Euro to the members with LP1 and between 12 and 15 Euro to the members with LP3. The differences between the CG, MC, and Shapley methods remain unchanged, so MC and Shapley methods distribute around 19 Euro to LP1 and 18 Euro to LP3 members. For the members with the LP2 profile, these three methods allocate between 17 and 18 Euro to each member. The C-based and G-based maintain their extreme patterns for the gain distribution. The comparison between the value share allocation methods is shown in Figure 10.

The FI remains the same for all three methods. Analyzing the allocation after optimization, one can notice that all members receive an increased bonus of 10%–20%. Those with a moderate consumption (LP2 profile) have the greatest increase of the gain (around 3.1 Euro/

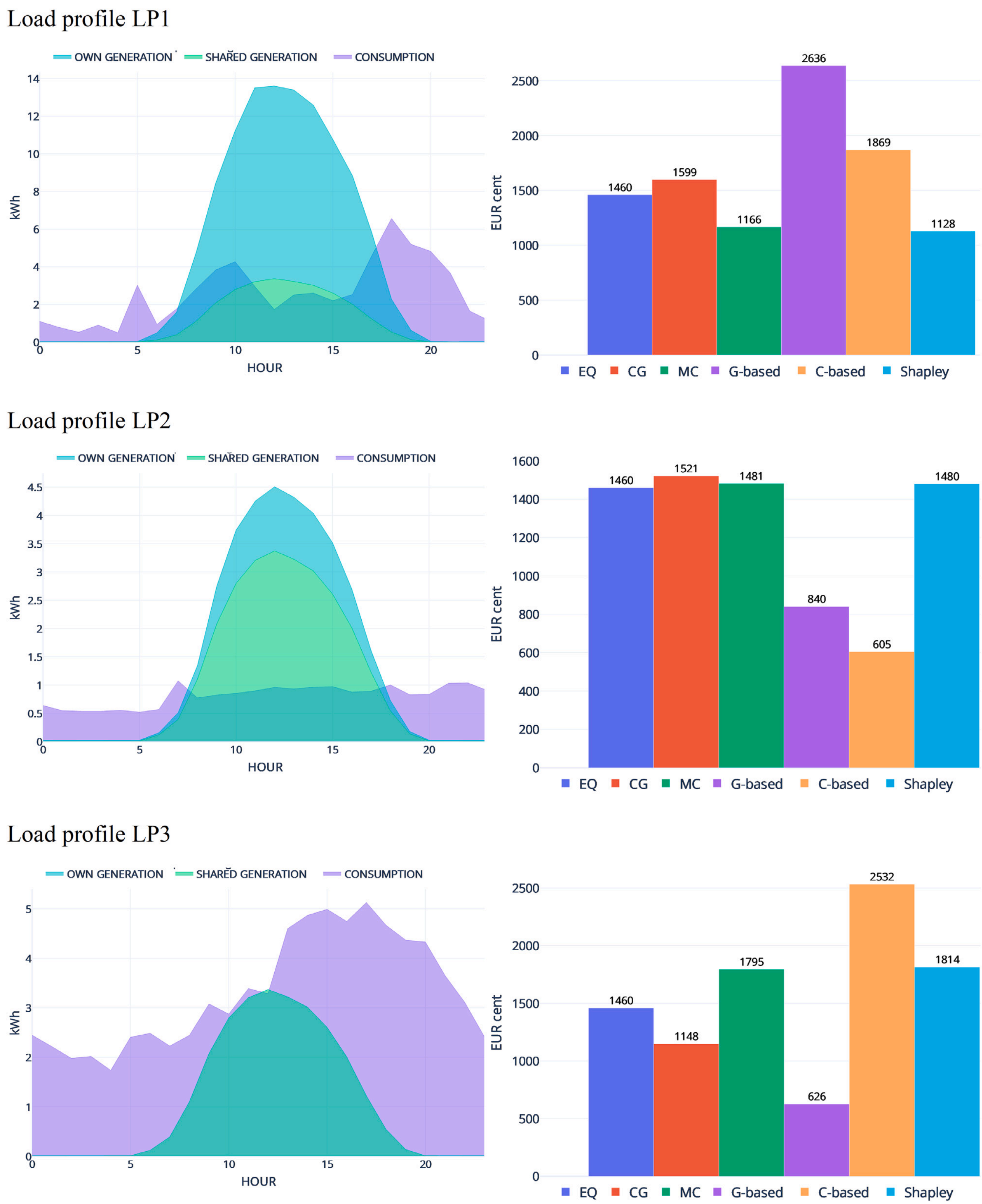


**Figure 6. Value share in July for each load profile of EC1**

The load profiles for LP1, LP2, and LP3 are represented in the left column, while the distribution of the value share is represented in the right column using the following methods: equal quota (EQ), the proposed method (CG), marginal contribution (MC), consumption generation-based (or G-based), consumption-based (C-based), and Shapley.

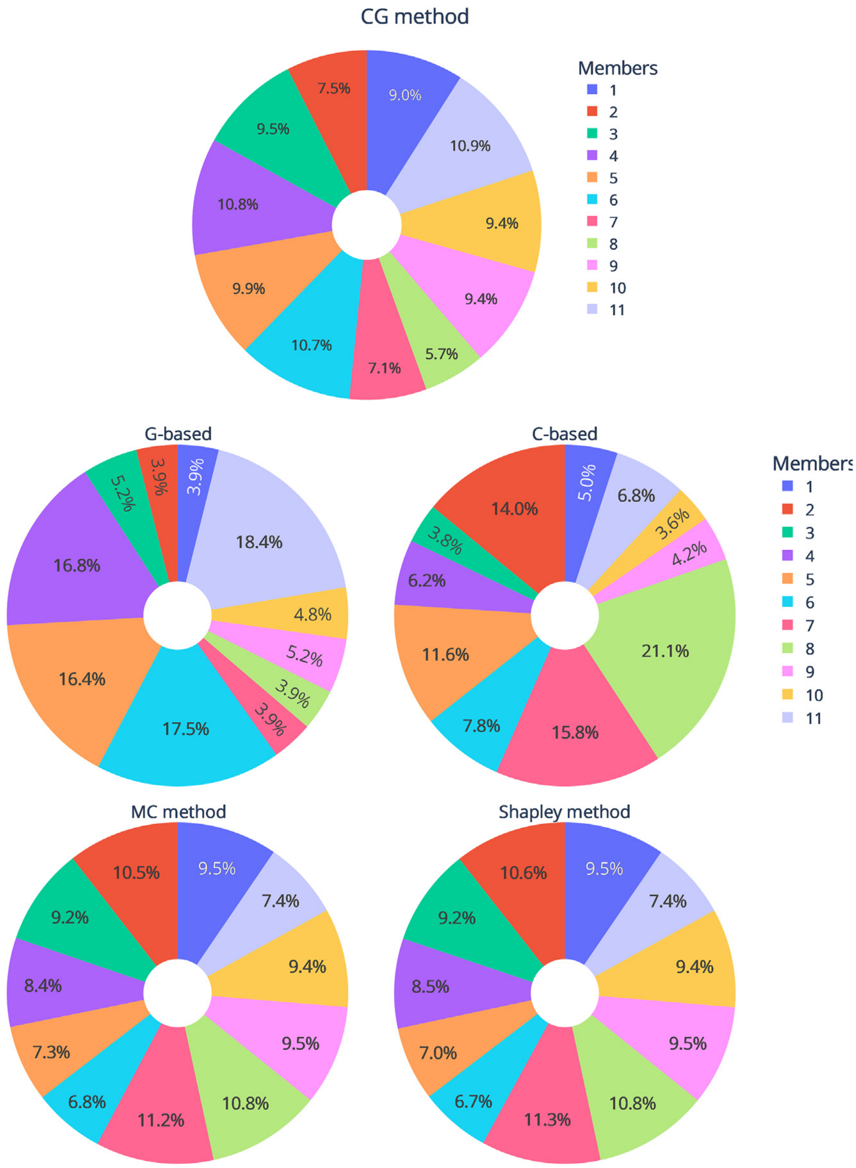


**Figure 7. Comparison between the gain distribution obtained by CG and the other methods for EC1 members in July 2021**

The gain obtained by applying the proposed method (CG) is compared with the gain obtained with following methods: consumption generation-based (or G-based), consumption-based (C-based), marginal contribution (MC), and Shapley.

month), followed by those with high generation belonging to LP1 profile (around 2.5 Euro/month). Those with a high consumption (LP3 profile) have the lowest increase of the gain between 1.5 and 2 Euro/month. Therefore, the new gain has a positive impact on all the members of the community and stimulates the changing behavior toward load optimization.

## Establishing the strategy of the communities

Since there are three different archetypes of communities, each of them may set its strategy differently. Thus, EC1 is heterogeneous, but it already has a high SSI value, especially during the summer, so it can choose a higher weight for $\alpha$ to maximize FI and attract more members. The value for $\beta$ can be set to 0.5 since SSI is high.

EC2 is a homogeneous community, therefore $\alpha$ can be set to 0.5, but $\beta$ can be increased up to 0.8.

EC3 is also heterogeneous, and it can choose to set equal weights for the coefficients: 0.65.

The algorithm SET_EC_STRATEGY proposed in method Section automatically calculates the gain and VS allocation corresponding to the VS methods and maximizes the optimization function for each time interval ($\Delta t$) corresponding to the winter or summer season. Since the results obtained for the MC and Shapley are similar and due to the fact that Shapley has a very high computational complexity, this method

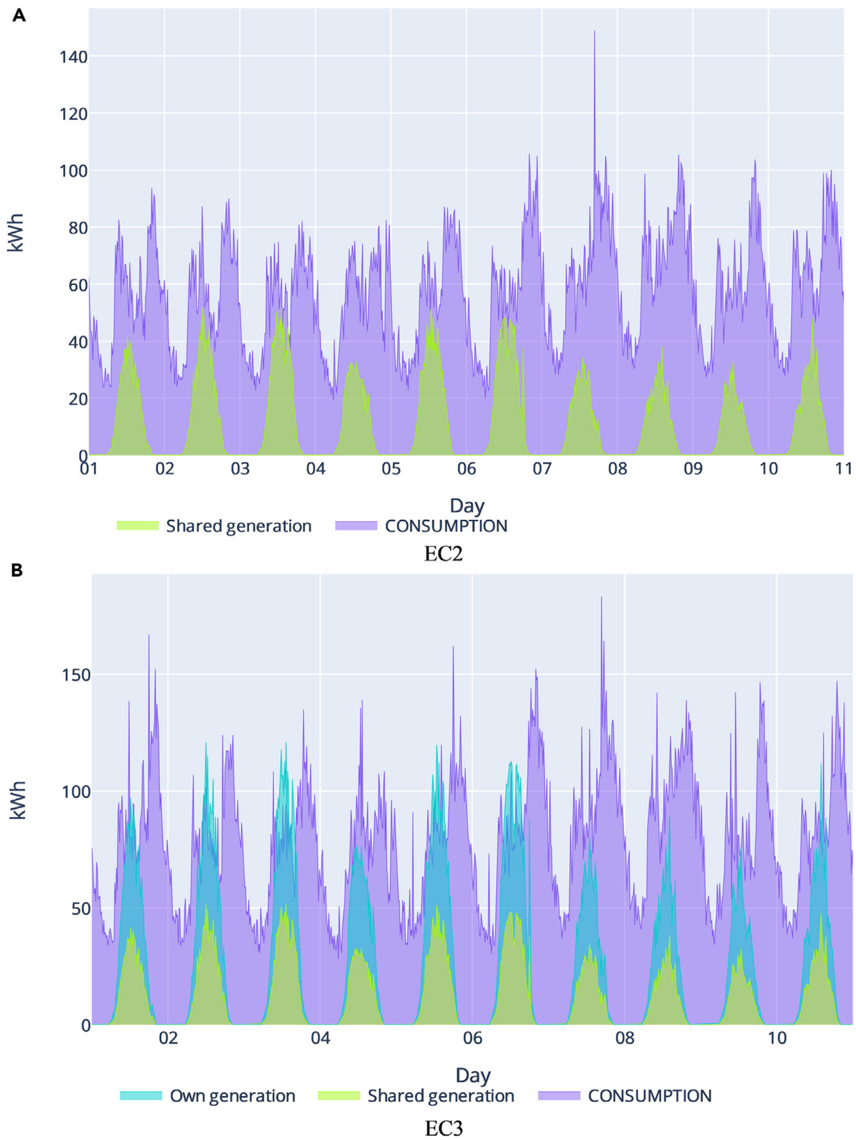


**Figure 8. Load profile and generation of EC2 and EC3 between 1st and 11th of July 2021**
Shared and own generation and consumption are represented for EC2 (A) and EC3 (B).

is not used for setting the strategy. Also, the G-based and C-based methods are not considered in this step since they provide an extreme allocation pattern, as demonstrated in the previous sections. Therefore, the algorithm is applied only to the following methods: EQ CG, and MC. The coefficients corresponding to the estimation of the increase of SSI for the methods ($\delta_{EQ}$,$\delta_{CG}$, $\delta_{MC}$) and the values of the optimization function ($f_{EC}$) obtained by using EQ, CG, and MC methods are centralized in Table 2. The coefficients $\delta_{EQ}$,$\delta_{CG}$, and $\delta_{MC}$ are set according to the findings from results. Thus, for EQ the coefficients are set to 0 since the method distributed equally the gain, for MC they are set to 0.5 since the method does not encourage the surplus contribution but considers the contribution to the total payment, and for CG the values are set to 0.7 since it directly encourages the surplus contribution.

As can be noticed, the proposed CG method obtained the highest value of the optimization function in all scenarios, since it has a high FI and stimulates the contribution of the members to the surplus and peak shaving. If $\delta_{CG}$ is set to 0.9 or even 1 then the $f_{EC}(CG)$ will have a higher value than the other two methods. For EC2 and EC3 in winter, SSI has a small value (0.02, 0.03 respectively) and the potential of these communities to increase their independence without investment in new shared generation is very low, as denoted by the values of all the optimization functions. Thus, in the case of EC2, any of the three methods can be selected during the winter season, whereas during summer CG and MC are more suitable for this community. In the case of EC3, for winter the proposed CG method is better, offering more gains to the members with their own generation sources and stimulating them to contribute more to the surplus.

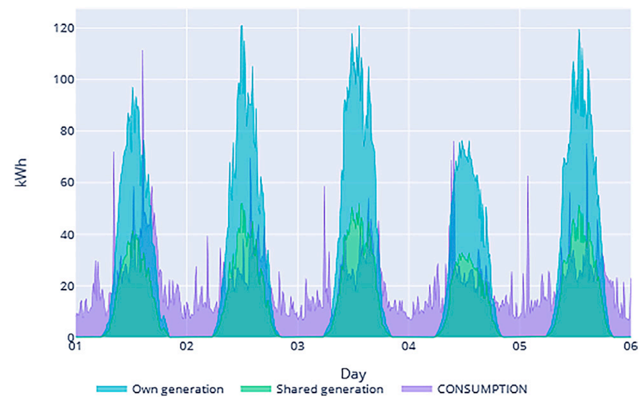


**Figure 9. Load profile and generation in July for EC1 after optimization**
Shared and own generation and consumption are represented for EC1 during 1st and 5th of July after shifting the consumption from hours with low generation to hours with surplus.

## DISCUSSION

The cost savings of the communities vary between 2% in the winter for EC2, which consists of a building with 114 apartments sharing a 50 kW PV capacity, and up to 70% in the summer for EC1 which consists of 11 houses with their own generation systems plus a 50 kW PV shared capacity. The cost savings and value share may contribute to the affiliation of prosumers who receive more revenue after joining the community. When analyzing the gain, it can be noticed that members with considerable surplus receive less in larger communities, regardless of the allocation method. For example, the members with LP1 and LP2 profile receive only 30% of the gain when switching from EC1 to EC3. Therefore, they are not encouraged to join such communities and may form smaller associations. On the other hand, the EC2 consumers benefit from joining EC1, since their individual gain increases from 2.9 to 4.3 Euro per month in the summer season. One measure to prevent the emergence of small coalitions is to set up local energy markets to trade the surplus and obtain a higher revenue.

The load optimization has a positive impact on the community value. By shifting the consumption from load peak to the hours with high generation availability, the gain of the community increases by 20% from 161 Euro to 191 Euro in July. In this case members gain up to 3 Euro per month, being stimulated to optimize their consumption and maximize the consumption from shared generation.

The paper compares several allocation methods and proposes a value share method based on the individual contribution to the surplus or deficit, or the community. The cost saving and FI are evaluated on three types of ECs, and the results demonstrate that the proposed method has the highest FI, rewarding members that contribute to the community surplus more than the members with a high demand that increases the EC deficit. Therefore, the proposed method incentivizes the local generation and load reduction, which is adequate for the transition toward a sustainable consumption based on distributed renewable sources.

The proposed methodology is implemented as an algorithm that automatically determines the gain of the community and calculates the evaluation metrics. Based on the metrics (FI, SSI) and three coefficients selected by the EC management, the algorithm determines the objective functions corresponding to the VS method that are applied to distribute the gain. Then, it automatically selects the method that maximizes the objective function, therefore assisting the EC to set up its strategy.

When there is an excess of RES generation on summer days, there is a risk of overloading the distribution grid unless proactive steps are taken. One approach to address this issue involves incentivizing electricity consumption through flexible tariff rates and promoting a shift in consumption patterns, primarily from the evening and morning hours to the midday period. Achieving this goal necessitates not only the implementation of intelligent dynamic pricing structures but also the integration of controllable appliances and the optimization of their operating schedules. The aim is to align energy usage with its availability and to capitalize on any surplus energy within the local community.

In the context of FITs, it is essential to note that certain countries offer more competitive rates to ECs for the surplus electricity they feed into the grid compared to what individual customers receive. Therefore, it is advisable that the model encompasses distinct FIT structures: one tailored for individual consumers and another specifically designed for ECs. The authors acknowledge the potential for this differentiation in FITs as a consideration for future research or implementation.

### Limitations of the study

One of the limitations of the current research is that the VS does not include dynamic tariff structures, local markets, and effective integration of controllable appliances. As a future work, these aspects will be investigated in relation to VS methods, electricity markets, and flexibility models.

## STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

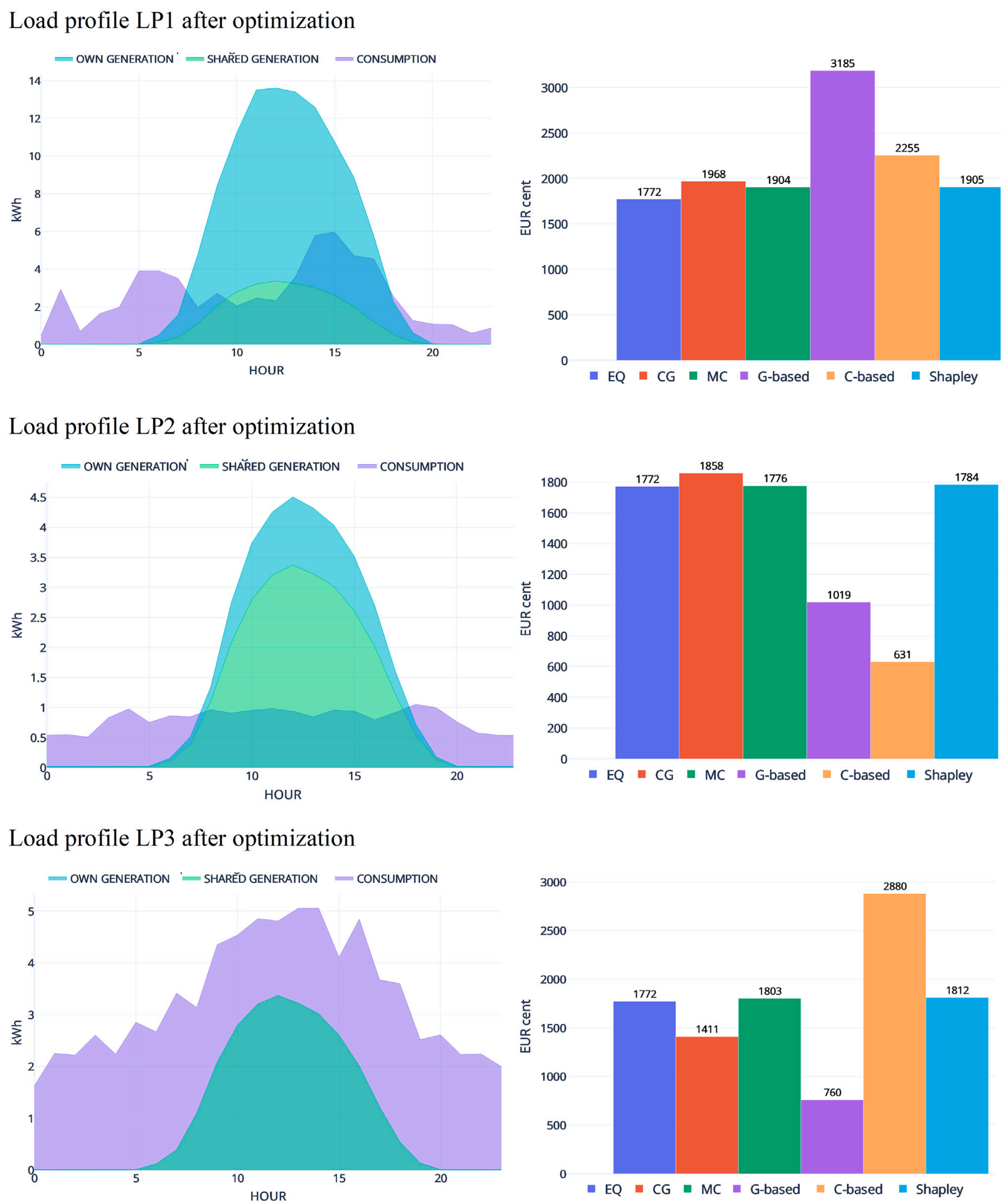


**Figure 10. Value share in July for EC1 after optimization for each load profile**

The load profiles after load shifting for LP1, LP2, and LP3 are represented in the left column, while the distribution of the value share is represented in the right column using the following methods: equal quota (EQ), the proposed method (CG), marginal contribution (MC), consumption generation-based (or G-based), consumption-based (C-based), and Shapley.

## SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.isci.2023.108687.

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## AUTHOR CONTRIBUTIONS

A.B. contributed to conceptualization, methodology, validation, formal analysis, investigation, resources, data curation, writing – original draft, writing – review and editing, visualization, and supervision. S.-V.O. contributed to conceptualization, validation, formal analysis, investigation, writing – original draft, writing – review and editing, visualization, and project administration.

## DECLARATION OF INTERESTS

The authors declare no competing interests.

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## STAR★METHODS

### KEY RESOURCES TABLE

| REAGENT or RESOURCE | SOURCE | IDENTIFIER |
|---|---|---|
| Deposited data | | |
| Sample of the records related to the consumption, own and shared generation of the EC3 in January 2021 | Authors (This paper) | https://github.com/AdelaBara/ValueShare_EnergyCommunities |
| Smart* Data Set for Sustainability | UMassTraceRepository | http://traces.cs.umass.edu/index.php/Smart/Smart |
| Software and algorithms | | |
| Python 3.11 | Python | https://www.python.org/downloads/ |
| Plotly Open Source Graphing Library for Python | Plotly | https://plotly.com/python/ |
| Pandas Library | Pandas | https://pandas.pydata.org/ |
| Code to reproduce the results of this study | Authors (This paper) | https://github.com/AdelaBara/ValueShare_EnergyCommunities |

### RESOURCE AVAILABILITY

#### Lead contact

Further information and requests for resources should be directed to Simona-Vasilica Oprea (simona.oprea@csie.ase.ro).

#### Materials availability

Not applicable. In this study no physical materials were generated.

#### Data and code availability

- Experimental data have been deposited on the Github platform and are publicly available as of the date of publication. They can be freely accessed and downloaded via https://github.com/AdelaBara/ValueShare_EnergyCommunities.
- The original code (script) has been deposited on the Github platform and is publicly available as of the date of publication. It can be freely accessed and downloaded via https://github.com/AdelaBara/ValueShare_EnergyCommunities.
- Additional information reported in this paper will be available from the lead contact upon request.

### METHOD DETAILS

The proposed methodology aims to provide an easy-to-follow decision model to automatically distribute the value or gain of an EC that is formed by affiliated members with or without their own generation sources, connected to the public grid through a single meter. The decision model supports the EC to determine its strategy to attract new members or increase its independence from the main grid. Figure S1 provides an overview of the interactions between the EC, its members and public grid, payment calculation, and value share allocation methods.

The proposed methodology consists of 4 steps as follows:

- *Step 1* – integrates the data from the smart meters that record the deficit and surplus of the members and the EC. The Time-of-Use (ToU) tariff for deficits and the Feed-In Tariff (FIT) for surpluses are applied to calculate the individual payment and the payment of the EC. The value share or the gain of the EC is determined as a difference between the total individual payments (without affiliation) and the payment of the EC.
- *Step 2* – distributes the gain of the EC to its members using several well-known value share allocation methods: equal share or equal quota, generation-based method, consumption-based method, marginal contribution, Shapley method. Also, the current approach proposes a novel method for value share allocation that distributes the gain according to the contribution of the members to the surplus and deficit of the EC.
- *Step 3* – evaluates the EC performance using the following metrics: cost savings, SSI, SCI, and FI. The metrics are used to assess the independence of the community from the main grid and to assess the fairness of the allocation method.
- *Step 4* – sets up the strategy of the EC based on the evaluation metrics and value share methods. The objective function of the EC is defined as a combination of the SSI and FI using weighting coefficients. Figure S2 shows the steps of the methodology.

### Calculating the payment and gain of the EC

Before affiliation, the revenue ($RevI_i^h$) and cost ($CostI_i^h$) of each member $i$ at hour $h$, depend on the individual consumption ($W_{c,i}^h$) and generation from own sources ($W_{g,i}^h$). The second term depends on the weather and season-dependent generation source availability, but regarding the first one – the higher the individual consumption of a member $i$ at hour $h$, the lower the revenue or the higher the cost.

The demand of each member $W_{d,i}^h$ can be defined as the difference between the individual consumption and own generation or storage:

$$W_{d,i}^h = W_{c,i}^h - W_{g,i}^h \quad \text{(Equation 1)}$$

In case $W_{d,i}^h$ is negative at hour $h$, it represents a surplus and, without affiliation, it is injected into the grid. Depending on the sign of $W_{d,i}^h$ the member $i$ has an individual cost or revenue. *ToU* is used to calculate the cost and *FIT* to calculate the revenue:

$$CostI_i^h = \begin{cases} W_{d,i}^h \times ToU^h, if\ W_{d,i}^h > 0 \\ 0, otherwise \end{cases} \quad \text{(Equation 2)}$$

$$RevI_i^h = \begin{cases} \left|W_{d,i}^h\right| \times FIT^h, if\ W_{d,i}^h \leq 0 \\ 0, otherwise \end{cases}$$

In case the members own parts of a VPP, then it is considered as a shared generation source ($W_{gs}^h$) and the individual quotas ($q_i$) are used to calculate the revenue from this source that is added to the initial revenue:

$$RevI_i^h = RevI_i^h + W_{gs}^h \times q_i \times FIT^h \quad \text{(Equation 3)}$$

The individual quotas ($q_i$) depends on the individual contribution of each member to the initial investment, maintenance, and operational costs of the VPP. The quotas can be equal in case all members contributed equally or can differ, being calculated by the EC management according to the individual contribution.

The effective payment of each member can be calculated as a difference between the individual cost and revenue:

$$PayI_i^h = CostI_i^h - RevI_i^h \quad \text{(Equation 4)}$$

Without affiliation, the total payment of the members is the sum of the individual payments:

$$Pay_0^h = \sum\nolimits_{i=1}^{n} PayI_i^h \quad \text{(Equation 5)}$$

After affiliation, the revenue and cost of the EC are calculated based on the records registered by the community meter considering the total surplus or deficit. Thus, if the energy generated by the EC at hour $h$ ($W_{gs}^h$) is higher than the total demand at hour $h$ ($\sum_{i=1}^{n} W_{d,i}^h$), then the revenue is calculated using the *FIT* rates, as following:

$$Rev^h = \left(W_{gs}^h - \sum_{i=1}^{n} W_{d,i}^h\right) \times FIT^h,\ if\ W_{gs}^h > \sum_{i=1}^{n} W_{d,i}^h \quad \text{(Equation 6)}$$

In case the total demand exceeds the generation at hour $h$ ($W_{gs}^h$), then the total cost of the EC can be calculated using the *ToU* rates, as following:

$$Cost^h = \left(\sum_{i=1}^{n} W_{d,i}^h - W_{gs}^h\right) \times ToU^h,\ if\ W_{gs}^h < \sum_{i=1}^{n} W_{d,i}^h \quad \text{(Equation 7)}$$

The total payment of the EC ($Pay_{EC}^h$) is either cost or revenue and can be expressed similar to the individual payment:

$$Pay_{EC}^h = Cost^h - Rev^h \quad \text{(Equation 8)}$$

The gain ($G_{EC}^h$) or the value share of EC represents the difference between the total payment of the members before affiliation and the payment of the community after affiliation:

$$G_{EC}^h = Pay_0^h - Pay_{EC}^h \quad \text{(Equation 9)}$$

Depending on the region or network operator, other fees (for grid connection, green certificates, etc.) may be included in the final billing, but to simplify the cost calculation and to make the allocation methods easier to understand, these fees are not included in the payment. It is important to note that technical losses or other network charges[65] were not included.

## Implementing the VS methods

Several value-sharing methods are depicted below:

1) ***Equal share or equal quota (EQ) allocation method*** distributes $G_{EC}^{h}$ in equal parts to the members, where $n$ is the number of EC members:

$$G_i^h = \frac{G_{EC}^h}{n} \quad \text{(Equation 10)}$$

The method distributes the value equally, without considering the contribution to the total demand/generation or to the payment of the community. It is a very simple method, easy to understand and applied, but brings no incentive to reduce the load or increase self-generation. The tariff rates do not influence the individual quota since all members receive an equal part of the EC value. The fairness of the method is questionable since the individual contribution is not considered.

2) ***Generation-based (G-based) method*** allocates the EC value accordingly to the generation quota ($q_i$) or capacity owned by each member:

$$G_i^h = q_i \times G_{EC}^h \quad \text{(Equation 11)}$$

3) ***Consumption-based (C-based) method*** distributes $G_{EC}^{h}$ proportionally with the individual consumption:

$$G_i^h = \frac{W_{c,i}^h}{\sum_{i=1}^{n} W_{c,i}^h} \times G_{EC}^h \quad \text{(Equation 12)}$$

The generation or consumption-based allocation methods reward only one side of the EC members, either prosumers or consumers, without encouraging the other side. It is a simple method that calculates the distribution very fast and is easy to understand and apply. The tariff rates do not influence the individual quota. The fairness of the methods is moderate since only some members of the group benefit more from the value share.

4) ***Marginal contribution (MC)*** of member $i$ is calculated as follows:

$$MC_i^h = G_{EC}^h - G_{EC-\{i\}}^h \quad \text{(Equation 13)}$$

Where $G_{EC-\{i\}}^{h}$ represents the EC value share without member $i$.

The community value is allocated proportionally with the marginal contribution:

$$G_i^h = \frac{MC_i^h}{\sum_{i=1}^{n} MC_i^h} \times G_{EC}^h \quad \text{(Equation 14)}$$

In this case, to allocate the value, additional calculations are required, and the method is not easy to understand and adopt. The difference between the tariff rates (FIT and ToU) influences the individual contribution to the payment. Therefore, if FIT is much lower than ToU tariff, then the method becomes unfair for the prosumers with high generation since their contribution is less than those with high demand. However, if the tariff rates are comparable, then the MC method is fair and stimulates the local generation and load reduction.

5) ***Shapley method*** is built on the MC method and allocates the value proportionally to the average of the marginal contributions of member $i$ to all possible coalitions ($S \subset EC$):[66]

$$G_i^h = \sum_{i \in S \subset EC} \left( G_S^h - G_{S-\{i\}}^h \right) \times \frac{(n-s)!(s-1)!}{n!} \quad \text{(Equation 15)}$$

The method considers all possible coalitions composed of EC members and calculates the marginal contributions to these coalitions. It is a very complex method with high computational requirements and difficult to understand and adopt by the members. To reduce the complexity, several approximation methods are proposed.[44]

Moreover, the MC and Shapley methods can become unfeasible for larger communities, and, in some cases, these methods negatively penalize some members. So, instead of receiving revenue, they need to pay more for being affiliated. This makes them exit the EC that becomes unstable.

6) **Proposed** ***allocation method****: consumption or load & generation profile-based value sharing method (**CG share**)*. The proposed method allocates the EC value based on the contribution of each member to the total surplus or deficit of the community. The surplus of the EC represents the total energy shared locally (without self-consumption) or injected into the grid that leads to the EC revenue. The deficit represents the total demand of the members that generates costs. Let us define the individual net energy measured by the smart meter of the consumer/prosumer as in Equation 16:

$$Wnet_i^h = W_{c,i}^h - W_{g,i}^h - W_{gs}^h \times q_i \quad \text{(Equation 16)}$$

Therefore, depending on the sign of the net energy metered, each member will have either surplus if the generation exceeds the consumption ($Wnet_i^h < 0$) or deficit if the consumption exceeds the generation ($Wnet_i^h > 0$).

The individual contribution to the EC surplus is determined as the ratio between the individual surplus and the total surplus of the members that is consumed locally or injected into the grid:

$$qS_i^h = \frac{Wnet_i^h}{\sum_{i=1}^{n} Wnet_i^h} \; (\forall) Wnet_i^h < 0 \quad \text{(Equation 17)}$$

The individual contribution to the deficit of the community is determined as the ratio between the individual deficit and the total deficit of the members that needs to be covered from the local generation or supplied by the grid:

$$qD_i^h = \frac{Wnet_i^h}{\sum_{i=1}^{n} Wnet_i^h} \; (\forall) Wnet_i^h > 0 \quad \text{(Equation 18)}$$

Then, the EC value is allocated proportionally with the individual contribution to the surplus and inversely proportional to the individual contribution to the deficit:

$$G_i^h = \begin{cases} \left(1 - qD_i^h\right) \times \dfrac{G_{EC}^h}{n}, \; if \; Wnet_i^h > 0 \\ \left(1 + qS_i^h\right) \times \dfrac{G_{EC}^h}{n}, \; if \; Wnet_i^h < 0 \end{cases} \quad \text{(Equation 19)}$$

The proposed method is easy to apply and does not require intensive or complex calculations. It is not influenced by the gap between the tariff rates and stimulates load reduction and self-generation. The members with a high generation and lower consumption are rewarded more than the members with a higher load. The lowest share is received by the members with the highest demand, as will be proven in Section 4 below.

## Calculating the evaluation metrics

In order to assess the above-mentioned methods, the following metrics are calculated:[39,44,48,67]

1) ***Cost Savings*** **(CS)** represent the amount of payment reduction compared to the initial payment without affiliation to EC. For each member, the cost savings for an interval *h* can be calculated based on the individual payment and the distributed gain using a specific allocation method as follows:

$$CS_i^h = \left(1 - \frac{PayI_i^h + G_i^h}{PayI_i^h}\right) \times 100 \quad \text{(Equation 20)}$$

The community savings are determined as a ratio between the total payment of individual payments without affiliation ($Pay_0^h$) and the total payment of the community after affiliation ($Pay_{EC}^h$):

$$CS_{EC}^h = \left(1 - \frac{Pay_{EC}^h}{Pay_0^h}\right) \times 100 \quad \text{(Equation 21)}$$

2) ***Self-Sufficiency Index*** **(SSI)** is the ratio between the energy used from local sources and the consumption. A value closer to 1 indicates that the local generation can meet the demand of the community. For each member, the SSI is calculated considering both shared and own generation sources:

$$SSI_i^h = \frac{Wused_{g,i}^h}{W_{c,i}^h} \tag{Equation 22}$$

Where $Wused_{g,i}^h$ represents the used energy from local generation and is the minimum value between the consumption and total generation for a member $i$, including own generation and generation quota:

$$Wused_{g,i}^h = \min_h \left( W_{c,i}^h, W_{g,i}^h + W_{gs}^h \times q_i \right) \tag{Equation 23}$$

The SSI for the community is determined in a similar mode using Equation 22:

$$SSI_{EC}^h = \frac{Wused_{g,EC}^h}{\sum_{i=1}^{n} W_{c,i}^h} \tag{Equation 24}$$

Where $Wused_{g,EC}^h$ is the used energy from local generation and is the minimum value between the total consumption and total generation shared locally:

$$Wused_{g,EC}^h = \min_h \left( \sum_{i=1}^{n} W_{c,i}^h, W_{gs}^h + \sum_{i=1}^{n} W_{g,i}^h \right) \tag{Equation 25}$$

3) ***Self-Consumption Index*** **(SCI)** represents the ratio between the energy used from local sources and the total generated energy. SCI evaluates the amount of energy produced and consumed locally and can be calculated for each member using Equation 26 or for the community using Equation 27:

$$SCI_i^h = \frac{Wused_{g,i}^h}{W_{g,i}^h + W_{gs}^h \times q_i} \tag{Equation 26}$$

$$SCI_{EC}^h = \frac{Wused_{g,EC}^h}{W_{gs}^h + \sum_{i=1}^{n} W_{g,i}^h} \tag{Equation 27}$$

A value of $SCI_{EC}^h$ closer to 1 indicates that the generated energy is consumed in the community and only a small amount is injected into the grid. A value of $SCI_i^h$ close to 1 indicates that the member $i$ contributes to the community generation, and his gain should reflect the contribution.

4) ***Fairness Index*** **(FI)** is calculated for the entire community and reflects the fair share of the allocation method. A value equal to 1 indicates that the allocation is equal between the members. FI can be calculated using Jain's fairness index[68] adapted for the energy community,[69] where $x_i^h$ represents the gain obtained by member $i$ related to the generation quota:

$$FI_{EC}^h = \frac{1}{n} \times \frac{\left( \sum_{i=1}^{n} x_i^h \right)^2}{\sum_{i=1}^{n} \left( x_i^h \right)^2} \tag{Equation 28}$$

$$x_i^h = \frac{G_i^h}{W_{g,i}^h + W_{gs}^h \times q_i} \tag{Equation 29}$$

To assess the fairness and the performance of the community, these evaluation metrics are calculated over longer periods, monthly or annually.

## Setting the strategy of the EC

The main objective of the EC is to have a stable community and to include members that can contribute to the increase of the total gain. The value share of the EC depends on the size of the community, load profiles of the members, capacity of the shared generation and the tariff rates applied to calculate the revenue and cost. To evaluate the value share allocation methods that are used to set up the strategy of the EC, a comparison of the methods in terms of complexity, understandability, scope and fairness is provided in Table S1.

Another objective of the EC, especially for the medium- and long-term, is to reduce as much as possible the dependency on the main grid and increase its Self-Sufficiency index. This aim can be achieved by increasing the shared generation capacity (installing new sources or storage capacity), incentivizing prosumers to invest in their own generation sources, or stimulating consumers to reduce or shift the load from peak hours to hours when local generation is available.

Taking into account these two objectives of the community, its strategy can be determined by two metrics: the Fairness index and Self-Sufficiency index. Thus, considering as input FI that reflects the fairness of the allocation methods and SSI that reflects the independence, the strategy of the community can be expressed by the following objective function:

$$f_{EC}(\Delta t, method) = \alpha \times FI_{EC}^{\Delta t} + \beta \times SSI_{EC}^{\Delta t} \times (1 + \delta_{method}) \qquad \text{(Equation 30)}$$

Where:

- $\Delta t$ is the time interval for the adoption of the strategy;
- *method* represents the VS allocation method belonging to the following list ['EQ', 'G- based', 'C-based', 'MC', 'Shapley', 'CG'];
- $\alpha$ and $\beta$ represent the coefficients that weight the values of FI and SSI;
- $\delta_{method}$ is a coefficient that estimates the increase of the independency in case *method* is applied.

The value of the $\delta_{method}$ coefficient can be selected considering the comparison in Table 1. Thus, for the EQ method, it can be considered 0 since the method does not stimulate peak shaving or contribution to the surplus of the EC. For the MC and Shapley methods, it can be set between 0.25 and 0.75, depending on the ToU and FIT rates. For the Generation or Consumption-based methods and for the proposed CG method, the coefficient can be set between 0 and 1, depending on the aim of the EC. Supposing that it intends to increase the generation, it sets $\delta_{method} = 1$ for the Generation-based and CG methods and $\delta_{method} = 0$ for the Consumption-based method.

Depending on the EC's interest, first it may choose to maximize FI, thus setting $\alpha$ close to 1 and $\beta \ll \propto$, to strengthen the community and attract new members. The following allocation methods can be selected based on this criterion: Marginal Contribution, Shapley allocation, or the proposed method (CG). After the community is stable, EC can increase $\beta$ to encourage its members to contribute more to the Self-Sufficiency index and gain independence from the main grid. A higher value of $\beta$ may lead to an increase interest in the shared generation and investments in new VPPs, may stimulate prosumers to install more local RES and may incentivize consumers to reduce their consumption. The following allocation methods can be selected for this purpose: Generation-based method and the proposed CG method. If the ToU rates are high at peak, then Marginal Contribution or Shapley allocation methods can also be selected. Regarding the gap between the ToU and the FIT, these rates usually depend on the regulator, the grid operator, or the supplier/retailer according to the countries' regulations. But if the ToU rate at night is set to a lower value, the energy sharing of a PV-based generation community might not be influenced as the PV systems do not generate at night. Therefore, it largely depends on the structure of the EC or the composition of its assets for generation, storage, as well as on the load profile of consumers.

The proposed methodology implements an algorithm (Algorithm 1) to set the strategy of the EC using the records from the smart meters (individual and EC) and the tariff rates. The algorithm is similar to a decision model that allows the EC management to calculate the payments, apply different VS allocation methods, and evaluate the metrics of these methods. Then, EC can simulate different scenarios for its strategy by setting $\alpha$, $\beta$ and $\delta_{method}$ coefficients and choosing the VS method that maximizes its objective function. The pseudo-code of the proposed algorithm is depicted below:

**Algorithm 1. Setting the strategy of the EC**

```
PROCEDURE SET_EC_STRATEGY (Δt)
  //Read data from individual and EC smart meters and tariffs (ToU, FIT):
  Input: W^h_{c,i}, W^h_{g,i}, W^h_{gs}, q_i, FIT^h, ToU^h for each i = \overline{1,n}, day ∈ Δt, h = \overline{1,24}
  //Set the weighting coefficients for the strategy
  Input: α, β
  //Step 1 - Calculate the individual costs, revenues, and payments for the entire period Δt:
  G^{Δt}_{EC} ← 0
  WHILE day IN Δt DO
    G^{day}_{EC} ← 0
    FOR h = 1 TO 24 DO
      Pay^h_0 ← 0
      FOR = 1 TO n DO
        IF W^h_{d,i} > 0 THEN
          CostI^h_i ← W^h_{d,i} × ToU^h; RevI^h_i ← 0
```

```
ELSE
  RevI_i^h ← abs(W_{d,i}^h) × FIT^h; CostI_i^h ← 0
END IF
RevI_i^h ← RevI_i^h + W_gs^h × q_i × FIT^h
PayI_i^h ← CostI_i^h − RevI_i^h
END FOR
Pay_0^h ← Pay_0^h + PayI_i^h
Pay_EC^h ← Cost^h − Rev^h
G_EC^h ← Pay_0^h − Pay_EC^h
G_EC^day ← G_EC^day + G_EC^h
END FOR
G_EC^Δt ← G_EC^Δt + G_EC^day
END WHILE
//Step 2 – Allocate the gain for the entire period using different VS methods
FOR method IN ['EQ', 'G-based', 'C-based', 'MC', 'Shapley', 'CG'] DO
  FOR each i = 1,n, day ∈ Δt, h = 1,24 DO
    CASE
    WHEN method='EQ' THEN G_i^Δt ← G_EC^Δt / n
    WHEN method='G-based' THEN G_i^Δt ← q_i × G_EC^Δt
    WHEN method='C-based' THEN G_i^Δt ← W_{c,i}^Δt / Σ_{i=1}^n W_{c,i}^Δt × G_EC^Δt
    WHEN method='MC' THEN
      MC_i^Δt = G_EC^Δt − G_{EC−{i}}^Δt
      G_i^Δt ← MC_i^Δt / Σ_{i=1}^n MC_i^Δt × G_EC^Δt
    WHEN method= 'Shapley' THEN
      Calculate the gain of all possible coalitions (S⊂EC)
      G_i^Δt ← Σ_{i∈S⊂EC} (G_S^Δt − G_{S−{i}}^Δt) × (n−s)!(s−1)!/n!
    WHEN method= 'CG' THEN
      Wnet_i^Δt = W_{c,i}^{hΔt} − W_{g,i}^Δt − W_gs^Δt × q_i
      Calculate qD_i^Δt and qS_i^Δt
      IF Wnet_i^Δt > 0 THEN G_i^Δt ← (1 − qD_i^Δt) × G_EC^Δt / n
      ELSE G_i^Δt ← (1 + qS_i^Δt) × G_EC^Δt / n
      END IF
    END CASE
  END FOR
  // Step 3 – Calculate evaluation metrics for each method
  FOR each i = 1,n, day ∈ Δt, h = 1,24 DO
    Calculate metrics for individual members: CS_i^Δt, SSI_i^Δt, SCI_i^Δt
  END FOR
  Calculate metrics for EC: CS_EC^Δt, SSI_EC^Δt, SCI_EC^Δt, FI_EC^Δt
  // Step 4 – Calculate the optimization function for each method:
  f_EC(Δt, method) ← α × FI_EC^Δt + β × SSI_EC^Δt × (1 + δ_method)
  END FOR
//Select the method that maximizes the objective function, where method IN ['EQ', 'G-based', 'C-based', 'MC', 'Shapley', 'CG']:
optimal method ← argmax(f_EC(Δt, method))
Output: optimal method^Δt
END PROCEDURE
```

## Nomenclature

*Variables*

| Variable | Description |
|---|---|
| $H$ | Hour |
| $N$ | Number of EC members |

(*Continued on next page*)

*Continued*

| Variable | Description |
|---|---|
| $I$ | Member of the community |
| $RevI_i^h$ | Revenue obtained as individual entity, without an affiliation to an EC |
| $CostI_i^h$ | Cost paid as individual entity, without an affiliation to an EC |
| $PayI_i^h$ | Effective payment of member $i$ as an individual entity |
| $W_{c,i}^h$ | Individual consumption |
| $W_{g,i}^h$ | Individual generation |
| $W_{d,i}^h$ | Individual demand ($W_{d,i}^h > 0$) or surplus ($W_{d,i}^h \leq 0$) |
| $ToU^h$ | Time-of-use tariff |
| $FIT^h$ | Feed-in tariff |
| $W_{gs}^h$ | Shared generation source of the EC |
| $q_i$ | Individual quotas own by the member $i$ from the shared generation source |
| $Pay_0^h$ | Total payment of the members without affiliation |
| $Rev^h$ | Revenue of the EC at hour $h$ |
| $Cost^h$ | Cost of the EC at hour $h$ |
| $Pay_{EC}^h$ | Effective payment of the EC |
| $G_{EC}^h$ | Gain or the value share of EC |
| $G_i^h$ | Individual gain |
| $G_{EC-\{i\}}^h$ | Value share without member $i$ |
| $MC_i^h$ | Marginal contribution of member $i$ |
| $S$ | Possible coalitions inside EC |
| $qS_i^h$ | Individual contribution (quota) to the surplus of the EC |
| $Wnet_i^h$ | Individual net energy measured by the smart meter. It is either surplus ($Wnet_i^h < 0$) or deficit ($Wnet_i^h > 0$) |
| $qD_i^h$ | Individual contribution (quota) to the deficit of the EC |
| $CS_i^h$ | Cost savings of member $i$ |
| $CS_{EC}^h$ | Cost savings of the community |
| $SSI_i^h$, $SSI_{EC}^h$ | Self-Sufficiency index of member $i$ and EC |
| $Wused_{g,i}^h$, $Wused_{g,EC}^h$ | Used energy from local generation corresponding to member $i$ and EC |
| $SCI_i^h$, $SCI_{EC}^h$ | Self-Consumption index of member $i$ and EC |
| $x_i^h$ | Gain obtained by member $i$ related to the generation quota |
| $FI_{EC}^h$ | Fairness index of the community |
| $method$ | VS allocation method |
| $\Delta t$ | Time interval: months, year |
| $f_{EC}(\Delta t, method)$ | Objective function of the EC |
| $\alpha, \beta$ | Weights or coefficients used for setting the strategy of the EC |
| $\delta_{method}$ | Coefficient that estimates the increase of the independence of the method |

## Acronyms

| Acronym | Description |
|---|---|
| CEP | Clean Energy Package |
| CG | Consumption (or Load)-Generation profile |
| CS | Cost Savings |
| EC | Energy Community |
| EQ | Equal Quota |

(*Continued on next page*)

*Continued*

| Acronym | Description |
| --- | --- |
| G-based | Generation-based |
| C-based | Consumption-based |
| EU | European Union |
| FI | Fairness Index |
| FIT | Feed In Tariff |
| HEM | Home Energy Management |
| IEM | Internal Electricity Market |
| LP | Load Profile |
| MC | Marginal Contribution |
| P2P | Peer-to-Peer |
| PV | Photovoltaic |
| RES | Renewable Energy Market |
| SCI | Self-Consumption Index |
| SSI | Self-Sufficiency Index |
| ToU | Time-of-Use |
| VPP | Virtual Power Plant |
| VS | Value Sharing |