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Costs Allocation in Energy Communities: An Insight on Users' Preferences

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Abstract—This paper aims to give an insight on the motivation of end-users within an energy community to encourage other users to join by sponsoring them. The proposed community organization is divided in two stages: first one for energy management and second one for costs allocation in an energy community (i.e. the way the overall bill is distributed among the members). In particular, two billing allocation approaches are proposed and account for end-user's preferences and their willingness to pay. Those strategies are based on an approach designed to set individual tariffs while preserving the properties of traditional allocation methods. This work gives perspective on different end-user's preferences and facilitates the understanding of energy communities farther than merely financial enterprises.

Index Terms—Energy communities, willingness to pay, cost allocation, energy management strategy.

I. INTRODUCTION

Energy communities (EC) have been emerging in the framework of the energy transition. The European Commission defined them as part of “citizen-driven energy actions that contribute to the clean energy transition, advancing energy efficiency within local communities.” Typically, EC consist in the aggregation of several individuals located in a near geographical area and connected through the same distribution grid. Those users can then share energy among themselves to reach more efficient energy usage collectively (both physically and economically). This is a way to add value to Distributed Energy Resources (DERs) located “behind the meter” traditionally managed to lower their owner's electricity bill. From the end-user perspective, one typical motivation to join an energy community would be potential further savings. Nevertheless, other motives can justify the adoption of this collective concept, such as transitioning to a more efficient energy management and furthermore reducing carbon emissions by increasing renewable energy supply, relocalizing energy production, fair energy access, among others [1]. In Europe, ECs have been commissioned at different stages, conditions and policies. Until now, 55% of the EU members have integrated EC in their energy policies and 24% of them are promoting it. The considered communities operate in a limited temporal window as well as geographical area: ranging from 500m proximity (in Spain) to a 2km radius (in France) for instance [2].

Energy communities can be operated with different energy management strategies, ranging from fully distributed, e.g peer to peer [3], to fully centralized. Other typical decentralized approaches include a community manager, that

supervises the community and is acting as intermediary between the EC members and the retailer [4].

In such cases, the main concern is to fairly allocate the costs while distributing the overall community electricity bill among the users. There are multiples approaches (theoretically infinite) to share the costs among the participants ensuring fairness and incentives for users to join an energy community and share resources collaboratively. Allocation of costs have been extensively studied as a cooperative/coalitional game by applying game theory, among other methods. Nash equilibrium and Shapley value account as fair and efficient methods to allocate resources in such competitive coalitions [5], [6] - for cooperative demand side management [7], and accounting for grid costs [8]. Others methods are based on cost causation theory [9] and self consumption [10], among others [11]. Ideally, allocation strategies shall account for the inherent interest of end-users to participate in EC. There is then a concern on increasing and attracting more users, and thus contribute to enlarge such communities.

Several studies on people's behavior and willingness to participate in energy communities suggest that the population is segmented into categories, such as *i*) early adopters, technodriver, people interested in investing in renewable energy and *ii*) price sensitive people, among many other profiles factors [12], [13]. This work proposes to consider those differences and include them in a methodology to allocate the costs in an EC.

The remaining of the paper is organized as follows: the community model and its energy management are presented in Section II. Section III describes the billing allocation approaches, and the proposed optimization model to consider end-user's preferences. The results are discussed in Section IV. Finally, the conclusions are disclosed in Section V.

II. SYSTEM MODEL AND CONSIDERED CASES

Consider a residential community of N members who are interested in investing in solar energy. Each member can be equipped with a photovoltaic panel and a storage system for their own needs -typically reduce their own energy bill with their conventional retailer (self-consumption, self-sufficiency). Each member n displays a given load and PV generation profile, $(P_{t,n}^l)$ and $(P_{t,n}^{pv})$ respectively. The energy storage system may charge $(P_{t,n}^{b-})$ and discharge $(P_{t,n}^{b+})$ according to the implemented management strategy which ultimately impacts the power exchanges $(P_{t,n}^{g+}$ and $P_{t,n}^{g-})$ with the main grid for given load/generation profiles.

Eq. 1 to 8 model the energy flows within the community with specific operating constraint for the storage - i.e. avoid simultaneous charge/discharge with the binary variables ($u_{t,n}^b$) and state of charge (SOC) update with the storage efficiency $\eta \sim 95\%$.

$$P_{t,n}^{g-} + P_{t,n}^{pv} + P_{t,n}^{b+} = P_{t,n}^{g+} + P_{t,n}^{b-} + P_{t,n}^l \quad (1)$$

$$P_{t,n}^{g+} \leq u_{t,n}^g \cdot P_{max}^g \quad (2)$$

$$P_{t,n}^{g-} \leq (1 - u_{t,n}^g) \cdot P_{max}^g \quad (3)$$

$$P_{t,n}^{b+} \leq u_{t,n}^b \cdot P_{max}^b \quad (4)$$

$$P_{t,n}^{b-} \leq (1 - u_{t,n}^b) \cdot P_{max}^b \quad (5)$$

$$SOC_{t+1} = SOC_t + \left(\eta \cdot P_{t,n}^{g-} - \frac{P_{t,n}^{b+}}{\eta} \right) \cdot \frac{dt}{E_{max}^b} \quad (6)$$

$$SOC_{min} \leq SOC_t \leq SOC_{max} \quad (7)$$

$$SOC_{t=0} = SOC_{t=T} \quad (8)$$

A. Individuals case

In the case where there is no coalition, i.e. no energy community, each individual trade electricity with the retailer solely, as shown in Fig. 1.

Electricity consumption is charged at the retail price π_t^- , and the electricity generation can be sold at price π_t^+ . Both prices are determined by the retailer considering different factors, policies and regulations [11]. In this work, both purchase and selling prices are considered to be flat. Furthermore, assumption is made that individuals are interested in their own profit, their main concern being to reduce their energy imports depending on the purchase price, while uptaking additional revenue by exporting/selling their potential surplus to the grid.

Thus individual battery is operated in order to minimize the overall bill expresses as follows:

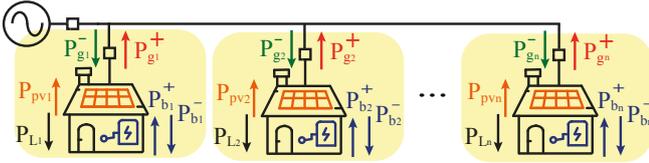


Fig. 1. Conventional power management for individuals.

$$\sum_n \min CI_n = \sum_n \min \left(\sum_t (\pi_t^- \cdot P_t^{g-} - \pi_t^+ \cdot P_t^{g+}) \cdot dt \right) \quad (8)$$

B. Energy community

An EC acts as a single entity interacting with its supplier, purchasing (P^{c-}) and selling the surplus (P^{c+}). Internally there are energy exchanges between the users, which influence the overall community exchanges with the main grid. Figure 2 depicts a scheme of an energy community, in which the dashed lines show the aggregated power.

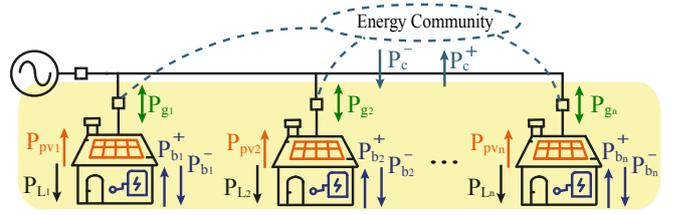


Fig. 2. Energy community scheme

The overall optimization problem in that case is described as follows with the minimization of the net community energy.

$$\min CC = \sum_t (\pi_t^- \cdot P_t^{c-} - \pi_t^+ \cdot P_t^{c+}) \cdot dt \quad (9)$$

$$\text{s.t. } P_{t,n}^g - P_{t,n}^{pv} - P_{t,n}^{b+} + P_{t,n}^{b-} + P_{t,n}^l = 0 \quad (10)$$

$$P_{t,n}^{c+} - P_{t,n}^{c-} = \sum_n P_{t,n}^g \quad (11)$$

$$P_{t,n}^{c+} \leq u_{t,n}^c \cdot P_{max}^c \quad (12)$$

$$P_{t,n}^{c-} \leq (1 - u_{t,n}^c) \cdot P_{max}^c \quad (13)$$

$$(4) - (8)$$

III. BILLING ALLOCATION IN AN ENERGY COMMUNITY

This section is dedicated to the billing approaches that integrate the willingness to pay of the users. The cost allocation is performed monthly and is based on the individual energy consumption and sharing management of the members in the EC. Thus, each end-user can save money simply by participating in the energy community. Equations 14 and 15 show the monthly net energy exports and consumption of the end-users, respectively.

$$E_n^{m+} = \sum_t^{month} P_{t,n}^{g+} \cdot dt \quad (14)$$

$$E_n^{m-} = \sum_t^{month} P_{t,n}^{g-} \cdot dt \quad (15)$$

In this work we apply the cost allocation in two consecutive steps. First we use the concepts of *proportional cost allocation* and *equal allocation of non-separable value (EANS)* to design a base bill repartition. The later will be used in an optimization model which considers user's preferences and willingness to give incentives to disengaged users by reducing their own savings.

A. Proportional-based Bill Allocation:

The first proposed billing allocation is based on the idea of Nash equilibrium, in which the resources are shared proportionally among the members of the EC, while considering the lowest cost users would have obtained by themselves without being part of a community - i.e. CI_n^* . Equation 16 describes the bill allocation while considering users exporting more than their amount of imported energy. Hence, their net commodity costs are negative, meaning that the retailer is paying for their energy surplus. In case all the members of the EC are solely consumers, i.e. their PV generation do not surpass their energy consumption, this rule is the equivalent to the typical proportional-based

bill allocation [8]. However, this repartition leads to equal savings for all participants, which may account as an unfair allocation, since each user have different load and PV profile and therefore the savings should be allocated accordingly.

$$b_n = CI_n^* - \left(\frac{|CI_n^*|}{\sum_n |CI_n^*|} \cdot \left(\sum_n CI_n^* - CC^* \right) \right) \quad (16)$$

B. EANSV-based Bill Allocation:

The separable costs are the individual costs before being part of a coalition, and the non-separable costs represent the difference between the total coalition costs and the sum of the separable costs [14]. Among many methods to allocate the non-separable costs, the EANSV assigns to each end-user their separable costs and then split equally the non-separable costs among the agents. Based on this approach, Eq. 17 simplifies the calculations and distributes the costs accounting with end-user's initial net costs to fairly allocate the new costs.

$$b_n = CI_n + \frac{(CC^* - \sum_n CI_n)}{N} \quad (17)$$

C. Considering End-user's Preferences

An optimization model is designed with the aim of allocating costs and finding an adequate price for the given consumption/generation of the energy community, which is based on the concept of centrally sharing and managing the resources, by an aggregator or a community manager. The notion of willingness to save of each end-user is denoted with the variable S_n - saving compared to the individual case with no community. In this sense, the end-user can set her/his preferences to save more, if the interest is on profit for instance, or save less but consume more electricity produced with renewables, a "greener" approach.

The new bill will be computed as follows:

$$C_n = (\lambda_n^- \cdot E_n^{m-} - \lambda_n^+ \cdot E_n^{m+}) \quad (18)$$

In which the prices λ_n^- and λ_n^+ are the variables in the following optimization model:

$$\min (\lambda_n^- - \pi_n^-)^2 + (\lambda_n^+ - \pi_n^+)^2 \quad (19)$$

$$\text{s.t. } \sum_n C_n = CC^* + G \quad (20)$$

$$\forall n \in WS :$$

$$0 \leq C_n \leq b_n \quad \forall CI_n \geq 0 \quad (21)$$

$$CI_n = C_n \quad \forall CI_n \leq 0 \quad (22)$$

$$\forall n \in NWS :$$

$$b_n \leq C_n \leq CI_n + |CI_n| \cdot S_n \quad \forall CI_n \geq 0 \quad (23)$$

$$CI_n \leq C_n \leq CI_n + |CI_n| \cdot S_n \quad \forall CI_n \leq 0 \quad (24)$$

in this model the final prices are compared with the initial ones. The idea behind this approach is to give tools to the community manager to allocate costs and charge each end-user independently accounting for their respective net consumption. Designing individual tariffs within the EC.

$$G = \gamma \cdot \left(\sum_n C_n - CC^* \right) \quad (25)$$

Additionally, the EC could aim at redistributing the total bill and simultaneously save some percentage γ of the earnings to further invest in EC assets, which is enforced with 25. Such savings could be further used to invest in new DERs in the community.

Moreover, the constraints 21 and 23 are designed to account for users with consumption greater than generation (i.e. base bill is positive). Therefore, depending on their preferences, on one hand, if they are not willing to save (set WNS) their bill will be between the base bill allocation and their initial bill when acting individually (CI_n) plus an extra percent (S_n), see 23. On the other hand, if the users aim at saving (set WS), then their bill will be at most the base bill allocation, see 21.

Similarly, when an end-user is producing more than its consumption (i.e. base bill is negative), then the model is designed to consider it with constraints 22 and 24. On one side, since the end-user is already producing and selling its generation, then these earnings are not reduced, however, it also means that the end-user will not profit more by joining an EC, this is enforced by 22. On the other side, if the end-user is not willing to save and subsidize others, then he will pay the same as he would selfishly obtain without cooperation or a percentage more, see 24.

IV. RESULTS AND DISCUSSION

The proposed framework is tested over an actual demonstrator of an EC, which includes seven households located in Le Cailar, south of France. Historical data collected for the month of March 2021 at a 30min time step, consist of power consumption and PV production profiles. The resources are managed as described in Section II, end-users independently trading with the retailer, and users within an EC sharing the resources as one entity. Management strategies are run in an offline mode, a posteriori, with deterministic profiles for the load and generation. See Fig. 3 for a comparison of individual energy management and the energy community centrally managing the resources. Notice that the EC purchases less power in the off sun hours (i.e. positive power), and sells less than not being in a EC, due to self-consumption within the EC before trading with the retailer, which allows a reduction in the individual bill.

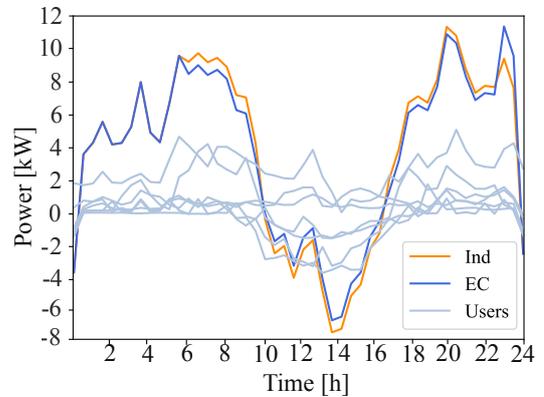


Fig. 3. Net daily power from individuals and community.

Based on the end-user's preferences, we assume that a percentage of all end-users within the EC are not willing

to save (*set NWS*), and to support other users (i.e. those who are not willing to pay, *set WS*). The costs of net electricity for each end-user are shown in Table. I, where the initial costs (*IC*) can be compared with the final costs (*FC*), along with the bill increase (*BI*), for both base cost allocations, *i*) proportional-based bill allocation (*Pr*), and *ii*) equal allocation of non-separable values (*EANSV*). The results are shown for a combination of users *NWS*: 2, 3, 5 (highlighted in red). In this case, the total cost of acting individually is 408.31€, while in an EC is 322.01€ - i.e. a bill decrease of 21.13% can be expected when DERs are operated in a community mode, i.e maximum earnings of 86.29€.

As already mentioned, from those results obtained with the first step, two methods are proposed to perform the costs allocation. Note that the community manager can set a percentage of the earnings by using $\gamma = X\%$, that can also be used as funds for investing in other energy assets and is not directly distributed among the members.

In the scenario exposed in Table. I, γ is set to be 10% of the maximum possible earnings (i.e. the difference between the final costs and the base cost allocation: 8.629€). Hence, the final costs are shared according to user's preferences, since users 2, 4, and 6 are already not receiving a bill decrease nor increase (notice they could get a reduction as in column *Pr*), with this gap the rest of the members are subsidized, even if there are some users who are not willing to save.

TABLE I
NET COSTS OF USERS [€] WITH $\gamma=10\%$

User	IC	Pr	FC	BI
1	118.44	101.06	96.38	-18.63%
2	-28.50	-32.68	-28.50	0.00%
3	51.38	43.84	43.84	-14.68%
4	-28.31	-32.47	-28.31	0.00%
5	188.14	160.52	160.65	-14.61%
6	-33.00	-37.85	-33.00	0.00%
7	140.16	119.59	119.59	-14.68%
Total:	408.31	322.01	330.64	-19.02%

Two approaches for bill allocation are applied to the study case and visible in Table. II - proportional-based (*Pr*) and *EANSV*-based (*EANSV*)- for the same result obtained with the first step individual and community optimization. In this new set of simulation for the second phase (bill allocation), the the community manager collects 80% of the earnings (setting $\gamma = 80\%$), forcing the users in the set *NWS* to increase their bill. For (*Pr*) the share is proportional for all members. On the other side a fairer repartition is applied when using equal allocation of non-separable values (*EANSV*), since the non-separable costs are shared proportionally, allowing each user to be charged according to its net energy consumption, compare the bill increase for *Pr* and (*EANSV*). For both cases the final costs can be compared with the initial ones and a total bill reduction is still achieved (4.23%).

To highlight the results on the net costs showed in Table II, Fig. 4 displays the results of using the proposed approach with *EANSV*-based allocation. Note that end-users 2, 4 and 6 do not perceive a change in their bill as already mentioned,

TABLE II
NET COSTS OF USERS [€] WITH $\gamma=80\%$

User	Pr			EANSV	
	IC	FC	BI	FC	BI
1	118.44	101.06	-14.68%	106.11	-10.41%
2	-28.50	-28.50	0.00%	-28.50	0.00%
3	51.38	43.84	-14.67%	42.68	-16.94%
4	-28.31	-28.31	0.00%	-28.31	0.00%
5	188.14	216.37	15.01%	204.24	8.56%
6	-33.00	-33.00	0.00%	-33.00	0.00%
7	140.16	119.59	-14.68%	127.83	-8.80%
Total:	408.31	391.05	-4.23%	391.05	-4.23%

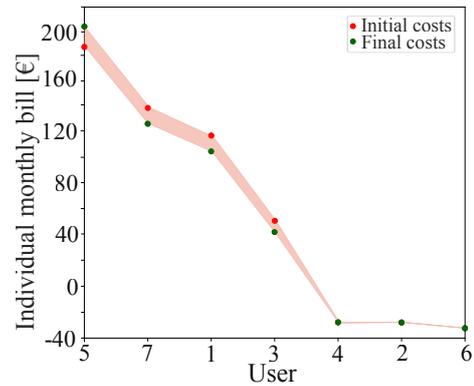


Fig. 4. Comparison of bill allocation using the proposed approach (*EANSV*-based) - users ranked with their bill in descending order.

nevertheless shown as well in Fig. 4. This gap allows the cost allocation to rely on end-user that consume more than their production (net consumers). Hence, even if such end-user are willing to support others by earning less, the method first allocates the resources to end-users who are net consumer over the month. Such as end-user 5, who is not willing to save and to support others, hence whose bill increases while all the others get a decrease. Additionally, although end-user 3 belongs to the set of users *NWS*, the obtained gap is enough not to increase her/his bill and furthermore get a reduction.

Furthermore, it is important to note that the proposed methods are more than just a cost allocation approach, it is designed to set individual tariffs within the EC, a task for the community manager, while preserving the properties of traditional allocation methods, such as efficiency and individual rationality. Furthermore, while it creates an environment where participants cooperate combining their individual and community interests, it also provides a tool to get revenues, and simultaneously encourages disengaged end-users to participate. In that context, Table III shows the personalized tariff for each individual, with a separate price for selling and purchasing (setting $\gamma = 80\%$) for the two cost allocation methods proposed. Hence, each end-user is charged according to its consumption/generation at a tariff close to the retailer price (*Init Price*). Notice that for end-users exporting more than consuming (i.e. net producer 2, 4, and 6) the selling prices are lower than the initial prices, which means that the model performing as expected, see 22 and 24. However, the net costs are equivalent to the initial ones, see Table II for $BI = 0\%$. Alternatively, the end-users who are net consumers get a set of tariffs that allow them to reduce their bill, for instance end-users 1 and 7 get a

reduction on their purchasing price, and an increase on the selling price. Which is reflected as a $BI = -10.41\%$ for end-user 1, and similarly for end-user 7 a $BI = -8.8\%$ when applying *EANSV-based* cost allocation.

TABLE III
TARIFF DESIGN ADOPTING THE PROPOSED APPROACH.

User	Purchasing price [€/kWh]			Selling price [€/kWh]		
	Init Price	EANSV	Pr	Init Price	EANSV	Pr
1	0.2062	0.198	0.191	0.1962	0.198	0.200
2	0.2062	0.221	0.221	0.1962	0.140	0.140
3	0.2062	0.210	0.214	0.1962	0.195	0.195
4	0.2062	0.219	0.219	0.1962	0.136	0.136
5	0.2062	0.221	0.233	0.1962	0.195	0.194
6	0.2062	0.222	0.222	0.1962	0.164	0.164
7	0.2062	0.192	0.180	0.1962	0.197	0.198

Finally, a sensitivity analysis is performed over the combination of users who are not willing to save and to support others, while deactivating the constraint fixing the earnings of the EC (i.e. 25). This is depicted in Fig. 5, where the difference between initial and final prices are evaluated, yielding to the community earnings. It is evident that the more users willing to participate in the set of end-user *nws* the more earnings the energy community will get.

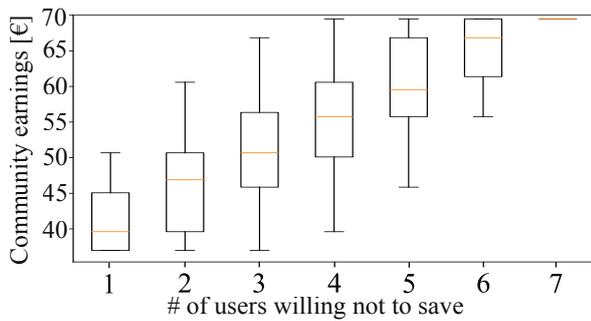


Fig. 5. Sensitivity analysis over γ . All scenarios where X number of users are willing not to save and to support others.

V. CONCLUSIONS

This paper explores the motivations of individual members within an energy community to advocate for others. A method is proposed to go beyond costs allocation in energy communities, and to provide a tool to design personalized energy tariffs according to user's preferences. This approach is based on an optimization model that sets the earnings of the community manager to a desired percentage, funds that could also be used to enhance the energy community assets. A sensitivity analysis is done over all the scenarios where the number of end-users willing not to save increase, leading to an average of minimum earnings of 46.35% of the total earnings, with at least one user willing not to save and support others. Future analysis should focus on a generalization of the proposed method by employing more profiles of end-users. A wider perspective could be depicted when comparing with other methods within local energy markets framework, such as peer to peer.

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