Comparing Value Sharing Methods for Different Types of Energy Communities

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***Abstract*—Energy communities combine assets of different community members and can create financial value from energy trade and from providing flexibility. Sharing this value among the community members can be done in various ways depending on the main objectives of the energy community and selecting the most suitable value sharing method for a particular energy community is not always straightforward. There are several, partly contradictory, requirements to be fulfilled that include fairness, stability, understandability, computational feasibility and ability to incentivize individual members to act in a way that benefits the whole energy community. In this paper, alternative energy community value sharing methods are compared from different viewpoints. The most suitable value sharing method for a particular energy community can be selected by first defining what are the main requirements for value sharing and then proceeding to a more detailed analysis of the value sharing method options that fulfill those requirements.**

Keywords—community energy, energy community, value sharing, cost allocation

I. Introduction

Energy communities (ECs) have been under active discussion during the recent years due to, on one hand, citizens becoming more interested and active in energy related topics and, on the other hand, political initiatives that aim to increase the amount of small-scale renewable generation and to encourage active prosumerism. European Commission has defined two types of energy communities: Renewable energy communities (RECs) are defined in [1] and citizen energy communities (CECs) in [2]. RECs are non-profit legal entities that can produce, store, sell and share renewable energy. CECs have similar characteristics but might be also able to operate grid infrastructure and are not restricted to renewable energy. For active consumer groups in same apartment buildings, [1] defines also Jointly acting renewables self-consumers. National legislation implementing the directives is either under work or already effective and may vary in different countries.

ECs can have quite different characteristics [3]. The simplest forms of ECs can be for instance apartment buildings that install solar panels on their roofs and share the production to individual apartments based on investment shares. On the other hand, ECs can be responsible for all the electricity related activities in a certain area including generation, distribution, consumption, aggregation, energy storage and all types of energy services [2]. It is clear that the needs vary substantially between different types of ECs and, hence, there is no universal solution for all ECs.

The motivational factors for forming an EC can be varied and include financial, self-sufficiency, environmental values and reliability of supply [4]-[5]. This paper concentrates on the financial side of EC operation i.e. savings in the member's electricity bill and/or maximizing the profits for generation units. ECs can create communal financial value through pooling the resources of individual members. This increases the self-consumption of local production and provides possibilities to operate actively on energy and flexibility markets. The created value can be shared among the community members in various ways depending on what is considered to be the main objective of the community and what kind of operation the community wants to incentivize. This paper introduces alternative EC value sharing methods and analyses their characteristics from different viewpoints. Emphasis is on electrical energy and sharing for instance heat resources is not included in the analysis.

II. Value Creation in Different Types of Energy Communities

The total electricity cost consists of distribution fee (paid to the distribution system operator (DSO)), energy fee (paid to the retailer) and taxes. ECs can create financial benefit for the members by decreasing any of the cost components.

Passive operation of a community creates value through combining the energy production and loading profiles. The main aim is to consume as much of the locally produced electricity as possible within the community i.e. maximize self-consumption. Savings can be obtained either in all the electricity cost components or only in the energy fee depending on local legislation and the scale and functionalities of the EC [3]. For instance in Finland, ECs located within one property do not need to pay distribution fees or taxes for the self-consumed energy [6].

If the community contains resources that can provide flexibility (controllable generation units, controllable loads or energy storages), the EC can actively increase its profit. The controllable resources can be used to optimize the self-consumption and to shift loading and/or generation to hours with a better price if electricity price is not static but based on for instance the wholesale market hourly prices. If a power-based distribution tariff is applied, peak load management can be conducted to decrease energy community costs. The

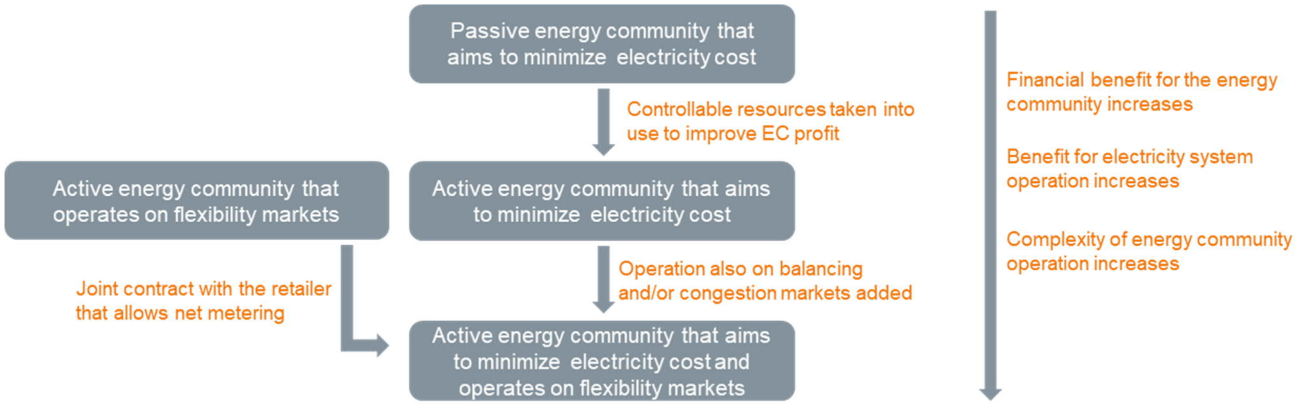

Fig. 1. Energy communities can have different functionalities. Passive energy communities are the simplest and require no changes to production and loading profiles. If controllable resources exist, they can be used to optimize the electricity use such that benefit in the electricity bill of the EC compared to the passive case increases or/and to participate to flexibility markets. The arrows in the figure depict what needs to happen to shift from one operational mode to a more profitable but also more complex one.

power-based pricing component of the tariff can be based, for example, on the peak load (i.e. highest hourly energy) over a month. Active ECs can also participate in flexibility markets (balancing and/or congestion management) which can be either their primary business model or a source of extra income in parallel with the functions aiming to minimize the electricity cost. In the latter case, EC decision-making process is a multi-objective optimization problem in multi-market environment and, hence, significant effort on proper coordination of activities is needed. The different EC functionalities are visualized in Fig. 1.

To conclude, ECs can create value for their members using different business models and the participation of the members to EC activities can vary. There are various methods to share this created value among the community members. It should be noticed that usually all EC members will aim to minimize their own electricity bill and, hence, the value sharing method has a significant effect on how the members will use their resources.

III. Value Sharing Methods

Value sharing method refers to a mechanism for distributing financial value created by EC operation to EC members based on a set of rules. During recent years, various value sharing methods have been proposed in publications [4], [7]-[13]. Each methodology comes with its own advantages and disadvantages and selecting the most suitable one for a specific case is never straightforward. Value sharing should be fair, stable, understandable, computationally feasible and incentivizing members to act in a way that benefits the whole EC. Stability means the EC's capability to retain all its members and is reached if none of the members could increase their benefit by leaving the community. Eight value sharing methods have been selected for further analysis in this paper. Although many other variations exist, this selection of methods already illustrates a wide range of differing incentive strategies, ranging from very simple methods to quite complex optimizations.

A. *Equal share of created value*

Equal share refers to a value sharing method, which allocates the value created by EC evenly and independently from individual investments and participation in local energy generation or storage [4]. All EC members receive the same benefit regardless of how they affect the costs of the EC. This inadvertently promotes only passive consumers and internal EC consumption. *Even share* is the most basic value sharing method, which is computationally simple and easy to understand. It also guarantees profits for every member if the EC is profitable. However, this EC setup is unstable, which means prosumers could increase their profits by breaking off the EC and forming smaller coalitions.

B. *Production capacity share*

Similar to the equal share method, capacity share method allocates a fixed share of the value created to each member [4]. The difference being, the share is proportional to the installed resource capacity, in most cases the rated power of PV system. This value sharing method incentivizes prosumers and their individual investment in distributed energy resources. However, this method entirely ignores the passive consumers of EC, which usually generate value for EC but receive no benefits. The method is computationally simple but unstable.

C. *Consumption based allocation*

This value sharing method is based on momentary consumption of electricity [4]. The value is shared proportionally to electric energy consumed. Contrarily to capacity share, consumption based method promotes local consumerism, ignoring the efforts of local production. This method does not ensure stability and is only suitable for production heavy ECs i.e. cases where production is substantially higher than consumption.

D. *Supply-demand ratio (SDR)*

SDR value sharing method is a local market mechanism used in peer-to-peer energy pricing in microgrids [7]. This method aims to find the middle ground between promoting active prosumers and consumers. It sets an internal price of electricity in EC based on PV availability with respect to local supply and demand. It encourages local energy consumption and generation while allowing prosumers to carry out price-based demand-response decisions. SDR is somewhat fair, intuitive, suited for real-time applications and computationally simple. It does not ensure EC stability but guarantees that every individual prosumer is better off compared to the conventional power-to-grid energy trading.

E. *Fixed share of production/storage*

The current interpretation of ECs in Finnish legislation is based on fixed shares of production and/or storage [6]. In this method, the EC members can invest in joint production units such as solar panels at the roof of an apartment building and can use their share of the production without paying distribution fees or taxes for it. The production share of each member is summed with their measured consumption for each balance settlement period and the billing is based on the computed value. The same applies also for storage unit output. The shares are usually divided based on the investment share of each community member. It should be noticed that this method differs from the others such that it is not exactly a value sharing method but rather a computational net metering application since the total EC value to be shared is not calculated at any point but all calculations are made separately for individual EC members.

F. *Marginal contribution (MC)*

This method distributes the value created in EC proportionally to individual marginal contribution of each member. The MC of member i to coalition S is an additional value it brings to the community. In other words, MC represents the EC value change if the member i left the coalition S,

$$MC(i, S) = v(S) - v(S - \{i\})$$

MC method does not guarantee the stability of EC nor does it ensure profits for every EC member. In fact, a member can be penalized, in terms of higher electricity import price, for being detrimental to the EC. However, MC method encourages active prosumerism and demand response, and it is computationally simple enough to enable also real-time applications.

G. *Shapley allocation*

Shapley allocation rule distributes the value created by EC proportional to the members expected marginal contribution to the community considering all the possible orders the members can join the community. In [8]-[10], value sharing in ECs has been done based on Shapley values.

Shapley allocation is one of the solutions for cooperative game problems, ensuring fairness but not necessarily stability. In convex cooperative games, value sharing based on Shapley values is the only stabilizing mechanism [11]. However, it has already been demonstrated that EC game is not convex [11]. The allocated value can also be negative and for larger ECs, computation becomes complex limiting the possibilities of real-time applications. Actually, calculation of Shapley values may need extensive computational burden since the number of possible orders to form an EC increases exponentially with the number of EC members. This method is not suitable for real-time application since it is based on numerical calculations and cannot be mathematically formulated for integration into prosumers decision process.

H. *Worst-case excess*

Cooperative game theory deals with problems where the competition is between groups of players. In cooperative game theory, the focus is on determining value sharing mechanism. In this concept, the set of all mechanisms stabilizing coalition consisting of all members is called core. Here, a mechanism is called stabilizing if it distributes the created value such that no subgroup of members has incentive to leave the coalition. Modeling EC as a cooperative game, the worst-case excess minimization concept provides an approach to find all value sharing mechanisms in the core [11]-[12]. This method is based on solving a linear optimization problem. The objective is minimizing the maximum dissatisfaction among all possible coalitions. Here, dissatisfaction value for a set of prosumers is equal to the total share allocated to the prosumers minus the value they can create if they leave the community to form a smaller community. In the problem, decision variables are the shares allocated to each member. The number of constraints in the problem is equal to the number of possible coalitions in the community, i.e., 2^n where n is the number of prosumers in EC. The method guarantees that no prosumer is penalized for joining an EC. Since the problem is in linear fashion, it can be solved via many available solvers. The number of constraints, however, increases exponentially with the number of EC members. This means that the huge number of constraints may limit the application of the method to small and medium-size ECs.

Besides the computational burden in larger ECs, the main shortcoming of this method is behind necessary assumption for modeling EC as a cooperative game with a non-empty core. The assumption says price of selling electricity to the grid is always less than the price of buying from the grid. This assumption is not always valid.

IV. Analysis of Value Sharing Methods

The value sharing methods introduced in the previous section range from very simple methods to advanced optimization algorithms. It is not always straightforward to select the best option for a specific EC case.

A. *Requirements for Value Sharing*

There are several characteristics that are required from EC value sharing methods. These include fairness, stability, understandability and computational feasibility. The methods should also be such that they incentivize members to act in a way that benefits the whole EC. The requirements are to some extent contradictory which makes it impossible to have one superior method for all types of ECs.

Fairness is difficult to define accurately. In many value sharing methods, fairness is defined based on direct effect of each member on the operational costs (total electricity bill) of the EC. The main idea is that members who operate in a way that decreases EC total costs more get a larger share of the created value. Marginal allocation and Shapley allocation methods are completely based on this definition of fairness and also supply-demand ratio and worst-case excess minimization methods to some extent. Calculating the contribution of each member naturally depends on the functionalities of the EC. As an example, self-consumption is maximized when generation and loading occur simultaneously and, therefore, members that have synergy with each other will be compensated more. If the community would include members with solar generation and members with electric storage heating, self-consumption could be increased by shifting the heating load from night-time to day-time and the members who would be willing to make this change should be rewarded.

TABLE I. COMPARISON OF VALUE SHARING METHODS

	Fairness	Stability	Understandability	Incentives for smart control	Computational requirements
Equal share of created value	All members get the same benefit regardless of how they affect the total costs of the EC and their additional investments.	Unstable. Smaller coalitions in which the benefit for an individual member increase can easily be found.	Very simple	Weak. Benefit that one member creates is divided equally to all even if the others would be totally passive.	Simple and fast to calculate, does not require a lot of computational resources
Production capacity share	Producer members get all the benefit. This takes into account the investments on production units but not the effect on EC total costs.	Unstable. All value is shared between members with production units. Members with only load don't receive any benefit.	Very simple	Very weak. Benefit that one member creates is divided to all producers based on capacity share. Members with only load would not get any benefit for their demand response actions.	Simple and fast to calculate, does not require a lot of computational resources
Consumption based allocation	Consumer members get all the benefit. This does not take into account the effect on EC total costs or investments.	Unstable. Members with low consumption can in many cases increase their benefit by forming communities without members with high consumption.	Very simple	Very weak. Benefit that one member creates is divided based on consumptions at that particular balance settlement period and, hence, low consumption members will not benefit from their smart control actions.	Simple and fast to calculate, does not require a lot of computational resources
Supply-demand ratio	Created value is shared based on local resource availability. The prosumer rewards are circumstantial, market based and thus fair from the effect on EC total costs viewpoint. Investments are not taken into account.	Unstable. Existing market conditions do not guarantee maximum payoff for most prosumers. However, it guarantees that all members are better off inside EC than outside.	Relatively simple. The value is shared within a local market and the prices for each time step are available to all.	High. Prosumers are heavily incentivized to adjust their demand to harmonize with the market.	Intermediate. Requirements are higher if a real time pricing is implemented instead of value distribution during the balance settlement period.
Fixed share of production/ storage	Production is divided between the members based on fixed shares and does not depend on the effect on EC total costs. Fair from investment perspective if the fixed shares are based on investment shares.	Stable. The share of production/storage that the member obtains is not dependant on the other members of the energy community.	Relatively simple. Easy to understand also afterwards how calculations were made.	Moderate. If members shift their consumption to times when production is high, they will save distribution fees and taxes.	Simple and fast to calculate, does not require a lot of computational resources
Marginal allocation	Benefit is divided between members based on the marginal contribution of each member to the community. This takes into account the direct effect on total EC costs but not the investments.	Unstable in many cases. Forming smaller communities can lead to higher benefits to certain members and the marginal value can in some cases be also negative.	Intermediate. The basic principle is easy to understand but the mathematics can feel complex for energy community members.	Relatively high. If members control their resources such that the energy community as a whole benefits, they will receive a larger share of the benefit.	Relatively simple to calculate and feasible also for larger energy communities.
Shapley	Usually considered the most fair method since it gives each member a share of the whole value that is proportional to the average of all his marginal contributions to all possible coalitions. This takes into account the direct effect on EC total costs but not the investments.	Unstable in many cases. Forming smaller communities can lead to higher benefits to certain members and the marginal value can in some cases be also negative.	Complex. The results are not necessarily intuitive and the mathematics can feel complex for energy community members.	Relatively high. If members control their resources such that the energy community as a whole benefits, they will receive a larger share of the benefit.	Complexity of calculations is intermediate and the requirements for computational capacity higher than for the methods above. Can become unfeasible for larger energy communities.
Worst-case excess minimization	The highest benefits go to members with high production and consumption and, hence, takes somehow into account the total EC costs and possibly also investments.	Stable. Members can not increase their benefits by forming smaller communities.	Complex. The results are not necessarily intuitive and the optimization algorithm is complex.	Moderate/relatively high. If members control their resources such that high production and high consumption coincide they receive higher benefits.	Computationally demanding and not suitable for larger energy communities in its basic form. With modifications, the computational time can be substantially decreased.

Another viewpoint on fairness is related to investments. A general principle is that the costs should go to those who cause them and the benefits should go to those who previously made the investment [14]. In methods that are based on direct effect on EC operational costs, investment viewpoint is not taken into account at all. It is possible to arrive to situations where a passive member who has not made any investments to renewable generation or control capabilities of its resources will receive significant benefits due to just having a suitable load profile for the EC. This could feel unfair even if the reasoning behind is valid and the passive member benefits the whole community. Production capacity share and fixed share of production/storage methods are dividing the benefits based on investments and are, therefore, cost-reflective.

The question of fairness in sharing the value among EC members is crucial because ECs that are considered unfair are unlikely to be formed at all. Fairness is also closely linked to stability and acceptability of the EC.

An EC is stable if there is no incentive for any subset of the members to leave the EC to operate either as individual prosumers or as a part of a smaller community. From purely mathematical viewpoint, an EC is considered stable when the financial gain for all members is the largest in the grand coalition (EC containing all the members) and none of them would financially benefit from forming a smaller coalition [11]-[13]. In practice, there are naturally also other factors affecting the stability including for instance inconvenience caused by the need to negotiate new contracts and to arrange practicalities related to the EC operation and social pressure to remain in the original EC. The main objective of the worst-case excess minimization method is to provide a value sharing method that is always stable.

Understandability and transparency of the value sharing method affect its acceptability among community members and are, therefore, also a characteristics to be taken into account when selecting the value sharing method. Simplicity of a method has also the benefit that simple methods are easy to implement and do not have high computational requirements and can, therefore, be implemented on any hardware that is available.

Value sharing methods should preferably be such that they incentivize individual EC members to control their resources such that the whole EC benefits. Methods that are based on fairness from EC operational cost viewpoint reward actions that benefit the whole community. It should be noticed that this kind of operation requires that the members have adequate information on the needed actions available and can plan and implement their actions accordingly. If the need for flexibility is not known, the automation systems of the members will not be able to activate their resources at suitable times. If value sharing is an offline process executed in retrospect and EC members would want to take it into account in their real-time activities, they would need to have a model of the value sharing method within their control systems. Another option would be that EC value sharing would be a real-time process that would provide necessary input information for individual EC members. This is possible only for value sharing methods whose execution time is short enough for real-time applications.

B. Comparative Analysis

The requirements for EC value sharing are partly contradictory and not all can be satisfied at the same time. For instance, Shapley that is generally considered the most fair method is not easily understandable and, also, does not guarantee stability of the EC. Comparison of the value sharing methods introduced in Section III is represented in TABLE I. This table can be used to support the selection process for a value sharing method for a particular energy community. The first step in this process is to define what requirements the particular EC considers the most important for itself. Thereafter, the most suitable value sharing options can be further analysed taking into account also practicalities such as availability of commercial solutions to implement the activity.

V. Conclusions

Value sharing in ECs is one of the key questions to be solved to enable large-scale deployment of ECs. Various value sharing methods have been proposed in publications, each having advantages and disadvantages. This paper analyses eight value sharing methods from different viewpoints and provides an overview on their characteristics. The requirements for value sharing used in the analysis in this paper include fairness, stability, understandability, computational feasibility and ability to incentivize individual members to act in a way that benefits the whole EC. The results of the analysis are presented as a table that can support the selection process for a value sharing method for a particular EC.

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