IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received May 4, 2021, accepted May 16, 2021, date of publication May 19, 2021, date of current version June 3, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3081871

Coalitional Game Theory Based Value Sharing in Energy Communities

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This work was supported in part by the Academy of Finland through the Distributed Management of Electricity System (DisMa) under Project 323696, and in part by the Business Finland through the Prosumer Centric Energy Communities—towards Energy Ecosystem (ProCemPlus) under Project 8211/31/2018.

ABSTRACT This paper presents a coalitional game for value sharing in energy communities (ECs). It is proved that the game is super-additive, and the grand coalition effectively increases the global payoff. It is also proved that the model is balanced and thus, it has a nonempty core. This means there always exists at least one value sharing mechanism that makes the grand coalition stable. Therefore, prosumers will always achieve lower bills if they join to form larger ECs. A counterexample is presented to demonstrate that the game is not convex and value sharing based on Shapley values does not necessarily ensure the stability of the coalition. To find a stabilizing value sharing mechanism that belongs to the core of the game, the worst-case excess minimization concept is applied. In this concept, however, size of the optimization problem increases exponentially with respect to the number of members in EC. To make the problem computationally tractable, the idea of clustering members based on their generation/load profiles and considering the same profile and share for members in the same cluster is proposed here. K-means algorithm is used for clustering prosumers' profiles. This way, the problem would have several redundant constraints that can be removed. The redundant constraints are identified and removed via the generalized Llewellyn's rules. Finally, value sharing in an apartment building in the southern part of Finland in the metropolitan area is studied to demonstrate effectiveness of the method.

INDEX TERMS Coalitional game theory, energy community, optimization problem, payoff allocation, prosumer, redundant constraint, value sharing, worst-case excess minimization.

I. INTRODUCTION

With the desire to achieve sustainable development, the Paris Agreement recommended all parties to put forward their best efforts to alleviate urgent threat of climate change [1]. In line with the agreement's ambitious goals, integrating renewable energy sources (RESs) in power systems serves as a pathway towards lowering greenhouse gas emissions. The European Union is targeting a 32% share for RESs in electricity consumption by 2030 and 64-97% by 2050. Having these targets in mind, penetration of solar energy is continuously growing since it is practically feasible to install solar panels on the rooftop of residential and commercial buildings. As a part of decarbonization efforts, the concept of energy communities (ECs) has been raised by the European Commission to empower end users, especially those who can generate, store, and sell renewable energy. This has been among driving forces for the formation of ECs in a couple of European countries [2]. In line with that, to alleviate the increasing complexity of power and energy management in systems with high penetration of distributed energy sources, local control schemes in ECs and microgrids beside global coordination schemes have attracted much attention [3]. Among different approaches for local control schemes, coalitional control concept has been recently used to have local controllers acting either cooperatively or independently at different times [4]–[6]. These all are among driving forces for the formation of ECs and microgrids.

EC is an entity formed by voluntary participation of prosumers with the goal to achieve economic, environmental, and social community benefits [7]. A prosumer is an individual/entity that can both produce and consume energy.

The associate editor coordinating the review of this manuscript and approving it for publication was Bin Zhou.

ECs can encourage self-consumption of locally generated energy thereby reducing network losses and operational costs [8]. Formation of ECs has been studied in the literature. In [9], an optimization model has been developed to minimize the cost of electricity consumed by a community of smart households. The study has demonstrated that forming an EC leads to lower aggregated costs compared to the case where the households would individually minimize their costs. In [10], coalitional game theory has been applied to model forming ECs considering the presence of flexible loads and uncertainties associated with renewable energy sources. The article has proved that forming ECs is almost always advantageous for the members. In [11], it has been shown that even simple energy consumers can gain cost savings from joining ECs. In [12]–[14], it has been shown that sharing costs and revenues of a common storage in an EC reduces the cost volatility for most prosumers, while the expected operational cost of the community remains unchanged. In [15], interactions among interconnected and autonomous microgrids have been modeled. In the study, it has been shown that formation of a community of microgrids leads to lower costs. In the works reported in [10] and [16], it has been proved that EC as a cooperative game is balanced, and energy cost savings from the cooperation can be shared such that no individual has incentive to leave the community.

There exist some approaches for sharing the value achieved by forming an EC among the members. The most prominent approaches are based on Shapley values, nucleolus concept, and the worst-case excess minimization concept [10] and [17], [18]. The Shapley values reflect coalition members' marginal impact on the value created by forming the coalition. Although value sharing based on Shapley values can be fair, it leads to a stable coalition only if the game is convex. In [9], [11], and [19], value sharing in EC has been done based on Shapley values. The study presented in [16] has demonstrated that value sharing based on Shapley values is not stabilizing in EC since the EC game is not convex. To tackle the issue, [16] has applied the nucleolus concept to allocate the extra benefit to the coalition members. It has compared the results with those achieved by the Shapley values and demonstrated that value sharing based on the nucleolus concept is stabilizing. In the study provided in [7], it has been observed that though value sharing based on the nucleolus concept provides a stabilizing mechanism, its calculation is highly intensive. Reference [10] has used optimization-based value sharing mechanisms to stabilize ECs. That study has compared nucleolus concept and the worst-case excess minimization problem. According to the study, the two methods lead to the same payoffs, but nucleolus is computationally intractable in larger communities. In [20]–[22], coalitions formed by wind power producers to reduce variability in their aggregated power thus improving their expected profit have been studied. In the studies, the worst-case excess minimization problem has been solved to allocate the extra profit to the coalition members. In the worst-case excess minimization problem, the number of constraints grows exponentially with the number of members in the coalition. This limits application of the worst-case excess minimization concept to smaller ECs. To overcome this limitation, [23], [24] have presented a stabilizing value sharing mechanism based on an analytical formula. The presented method is very effective since it provides a stabilizing mechanism without significant computational complexities. However, value sharing mechanism based on the analytical formula allocates the whole cooperation benefit to consumers if the community net consumption is negative. This may result in dissatisfaction of producers who have invested on local generation facilities. This is in clear contradiction with the global trend toward incentivizing investment on local generation facilities.

Since the EC game is not convex, it is likely that it has several stabilizing value sharing mechanisms. On the other hand, a value sharing mechanism is stabilizing if and only if it satisfies the constraints in the worst-case excess minimization problem. So, to find a fairer and still stabilizing mechanism, one may need to solve the worst-case excess minimization problem. The importance of searching for a value sharing mechanism that is both fair and stabilizing has been explained in [25]. However, the huge number of constraints in the worst-case excess minimization problem is a barrier. To fill the gap, this article proposes the idea of assuming the same payoff for prosumers with rather similar generation/consumption profiles. To do so, prosumers' profiles are clustered and similar profile and payoff are considered for prosumers in the same cluster. K-means clustering approach is applied and clusters' centroids are used to represent prosumers in each cluster. Doing so, several constraints in the worst-case excess minimization problem become redundant. Then, Llewellyn's rules are used to identify and remove redundant constraints to achieve a computationally tractable problem. The proposed method is applied to an apartment building in the southern part of Finland in the metropolitan area. Based on the results, computational burden of the problem can be decreased significantly without jeopardizing outcome accuracy if appropriate number of clusters is selected. Accordingly, the main contributions of the current paper can be summarized as follows:

- The formation of an EC is studied via coalitional game theory concept and different properties of the EC game are discussed.
- A computationally efficient procedure is developed to solve the worst-case excess minimization problem. This provides the opportunity to find a fairer and still stabilizing value sharing mechanism for ECs.
- The developed procedure significantly decreases size of the worst-case excess minimization problem without much affecting the results. This is demonstrated via applying the procedure to a real apartment building in the southern part of Finland.

The rest of this paper is organized as follows. In Section II, a brief description of coalitional game theory is presented. Section III describes the EC problem and presents a coalitional game for the problem. It also investigates properties of the game and presents a stabilizing value sharing mechanism for the game. In Section IV, evidences from numerical analyses are provided. Finally, Section V concludes the paper.

II. COALITIONAL GAME THEORY

This section provides a brief background for the coalitional game theory, key definitions, and relevant theorems. Coalitional game theory deals with problems where the competition is between groups of players. In coalitional games, the focus is mainly on predicting coalitions that may form and the payoffs. Coalitional game theory has been extensively used in different disciplines and several definitions and theorems related to coalitional games have been introduced [12] and [20]. Hereinafter, some of the definitions and theorems necessary to study the proposed game are reviewed. The interested reader may see [17], [18] for more detailed explanations on the topic.

Definition 1 (Coalition): Assuming $\mathcal{N} := \{1, 2, \ldots, N\}$ as the set of players, a coalition is any subset $\mathcal{S} \subseteq \mathcal{N}$. The set of all possible coalitions is defined as the power set 2^N of N.

Definition 2 (Grand Coalition): Grand coalition is a coalition with all players. Assuming $\mathcal{N} := \{1, 2, \ldots, N\}$ as the set of players, $\mathcal{N}$ itself is grand coalition.

Definition 3 (Coalition Value): Total value created by forming a coalition is called coalition value. Coalition value is also known as coalition payoff. Payoff and value are used interchangeably in this article.

Definition 4 (Value Sharing): A mechanism that describes how to share coalition value between the members is called value sharing or payoff allocation.

Definition 5 (Transferable Payoff): A coalitional game without any restriction on sharing coalition value between the members is a game with a transferable payoff.

Coalitional games with transferable payoff can be represented by a pair $(2^N, \upsilon)$ where 2^N is the set of possible coalitions of the game and $\upsilon : 2^N \rightarrow \mathbb{R}$ is the value function that assigns a value to each coalition $\mathcal{S} \subseteq \mathcal{N}$.

Definition 6 (Core): Core is the set of value sharing mechanisms for which no group of players has an incentive to leave the grand coalition. A game with empty core does not necessarily have a stable grand coalition since members may leave the coalition with the desire for a higher payoff.

Definition 7 (Super-Additive Game): A game is super-additive if in the game, value of a coalition cannot be improved by splitting it into two smaller coalitions.

Assuming two disjoint coalitions $\mathcal{S}$ and $\mathcal{T}$, super-additivity of a coalitional game can be mathematically evaluated by checking the following condition:

$$\upsilon(\mathcal{S}) + \upsilon(\mathcal{T}) \leq \upsilon(\mathcal{S} \cup \mathcal{T}) \quad \forall \mathcal{S},\ \mathcal{T} \subseteq \mathcal{N},\ \mathcal{S} \cap \mathcal{T} = \emptyset \tag{1}$$

Theorem 1: In a super-additive game, grand coalition has the highest created value [18].

Definition 8 (Convex Game): A game is convex if a marginal contribution of any player does not decrease if the player participates in a larger coalition.

Assuming grand coalition $\mathcal{N}$, coalition $\mathcal{T} \subseteq \mathcal{N}$, and coalition $\mathcal{S} \subseteq \mathcal{T}$, the convexity of a coalitional game can be evaluated by checking the following condition:

$$\upsilon(\mathcal{S} \cup \{i\}) - \upsilon(\mathcal{S}) \leq \upsilon(\mathcal{T} \cup \{i\}) - \upsilon(\mathcal{T}) \quad \forall i \notin \mathcal{T} \tag{2}$$

Theorem 2: A convex game has a nonempty core and Shapley values provide a stable value sharing mechanism inside the core [18].

Definition 9 (Balanced Game): A game is balanced if the weighted sum of values of coalitions containing player i is less than or equal to the value of grand coalition provided that the weights are inside [0, 1] and their sum is equal to 1.

Assuming grand coalition $\mathcal{N}$ and any arbitrary player $i \in \mathcal{N}$, balancedness of a coalitional game can be mathematically evaluated by checking the following condition:

$$\sum_{\substack{\mathcal{S} \subseteq \mathcal{N} \\ i \in \mathcal{S}}} \alpha(\mathcal{S})\, \upsilon(\mathcal{S}) \leq \upsilon(\mathcal{N}) \quad \forall \alpha \in [0, 1], \sum \alpha(\mathcal{S}) = 1 \tag{3}$$

Theorem 3: A balanced coalitional game has a nonempty core [18].

III. COALITIONAL GAME FOR ENERGY COMMUNITY

This section presents a value sharing mechanism for ECs based on coalitional game theory. The function of the value created by an EC and its properties are first discussed. Then, description of a coalitional game for the EC is followed by proposing a stable value sharing mechanism for the game.

A. VALUE FUNCTION IN ENERGY COMMUNITY

An EC consists of prosumers. Here, it is assumed that a consumer is also a prosumer with zero production. Similarly, the owner of a local generating unit is a prosumer whose energy consumption is negative. Although formation of EC can have different incentives, economic incentive of EC formation is considered in this article. With these in mind, the value created by an EC is mathematically formulated here.

Consider a group of N prosumers, i.e., $\mathcal{N} := \{1, 2, \ldots, N\}$, indexed by $i \in \mathcal{N}$. The power produced/consumed by prosumer i at time t is denoted by $p_i(t) \in \mathbb{R}$. It is assumed that all prosumers are hosted by a common bus in the electric power network. So, they are charged with common electricity prices. It is assumed that energy can be imported from the network at a non-negative price $\lambda \in \mathbb{R}_+$ (¢/kWh) and can be exported to the network at a non-negative price $\mu \in \mathbb{R}_+$ (¢/kWh). It is assumed that the price for importing electricity from the network is greater than or equal to the price for exporting electricity to the network, i.e., $\lambda \geq \mu$. Note that the assumption makes sense especially in networks with higher integration of renewable energy sources [10]. The same assumption has been made in many research works [10], [16], and [19]. On the ground of this assumption, there will be some individual prosumers who are willing to form EC $\mathcal{S} \subseteq \mathcal{N}$ and aggregate their production/consumption to reduce their net power exchange with the network. In other words, it is always economically profitable to exchange prosumers' extra produced power inside the community. The aggregate output corresponding to the EC formed by prosumers inside $\mathcal{S} \subseteq \mathcal{N}$ is calculated as follows

$$p_{\mathcal{S}}(t) = \sum\nolimits_{i\in\mathcal{S}} p_i(t) \quad \forall t \in T \tag{4}$$

Note that $p_{\mathcal{S}}(t)$ takes negative values if production by the prosumers exceeds their consumption at time t. The value created by coalition $\mathcal{S}$ on the time interval T is defined as

$$\begin{aligned}&\Pi\left(p_{i\in\mathcal{S}}(t)\right)\\&=\sum\nolimits_{t\in T}\sum\nolimits_{i\in\mathcal{S}}\left(\lambda p_i(t)^+ + \mu p_i(t)^-\right)\\&\quad-\sum\nolimits_{t\in T}\left(\lambda\Big[\sum\nolimits_{i\in\mathcal{S}} p_i(t)\Big]^+ + \mu\Big[\sum\nolimits_{i\in\mathcal{S}} p_i(t)\Big]^-\right)\end{aligned} \tag{5}$$

where $x^+ := max\{x, 0\}$ and $x^- := min\{x, 0\}$ for all $x \in \mathbb{R}$. In (5), the first term is the electricity cost of all individual prosumers in coalition $\mathcal{S}$ over time interval T if the prosumers do not participate in the EC, and the second term is electricity cost of EC $\mathcal{S}$ over time interval T. In the first term $\lambda p_i(t)^+/\mu p_i(t)^-$ is the value prosumer i should pay for importing/exporting power from/to the network at time t. Note that $\lambda p_i(t)^+$ and $\mu p_i(t)^-$ are respectively positive and zero if prosumer i imports power from the network at time t. They are respectively zero and negative if prosumer i exports power to the network at time t. The similar condition holds for $\lambda\big[\sum_{i\in\mathcal{S}} p_i(t)\big]^+$ and $\mu\big[\sum_{i\in\mathcal{S}} p_i(t)\big]^-$ and EC $\mathcal{S}$ aggregated power. It is worth mentioning that formation of EC may have some cost in practice. The cost can be divided into investment costs and operation costs. Investment costs can be caused by necessary changes in metering systems and facilities as well as contract design. Operation costs can be due to additional processes required for value sharing and billing inside the community. These costs are however overlooked in this study. This assumption is in line with the literature where no cost has been considered for EC formation [9]–[14].

The following Lemmas establish certain properties of Π.

Lemma 1: The function Π as defined in (5) is positively homogeneous. This implies that

$$\Pi\left(\alpha p_{i\in\mathcal{S}}(t)\right) = \alpha\Pi\left(p_{i\in\mathcal{S}}(t)\right) \quad \forall\alpha \in \mathbb{R}_+ \tag{6}$$

Proof: Using (5), $\Pi\left(\alpha p_{i\in\mathcal{S}}(t)\right)$ is as follows

$$\begin{aligned}&\Pi\left(\alpha p_{i\in\mathcal{S}}(t)\right)\\&=\left(\sum\nolimits_{t\in T}\sum\nolimits_{i\in\mathcal{S}}\lambda\alpha p_i(t)^+ + \mu\alpha p_i(t)^-\right)\\&\quad-\left(\sum\nolimits_{t\in T}\lambda\Big[\sum\nolimits_{i\in\mathcal{S}}\alpha p_i(t)\Big]^+ + \mu\Big[\sum\nolimits_{i\in\mathcal{S}}\alpha p_i(t)\Big]^-\right)\end{aligned} \tag{7}$$

which can be written as

$$\begin{aligned}&\Pi\left(\alpha p_{i\in\mathcal{S}}(t)\right)\\&=\alpha\Bigg[\left(\sum\nolimits_{t\in T}\sum\nolimits_{i\in\mathcal{S}}\lambda p_i(t)^+ + \mu p_i(t)^-\right)\\&\quad-\left(\sum\nolimits_{t\in T}\lambda\Big[\sum\nolimits_{i\in\mathcal{S}} p_i(t)\Big]^+ + \mu\Big[\sum\nolimits_{i\in\mathcal{S}} p_i(t)\Big]^-\right)\Bigg]\end{aligned} \tag{8}$$

which is equivalent to (6).

Lemma 2: The function Π as defined in (5) is super-additive. Assuming two disjoint ECs $\mathcal{S} \subseteq \mathcal{N}$ and $\mathcal{T} \subseteq \mathcal{N}$, Lemma 2 implies that

$$\Pi\left(p_{i\in\mathcal{S}\cup\mathcal{T}}(t)\right) \geq \Pi\left(p_{i\in\mathcal{S}}(t)\right) + \Pi\left(p_{i\in\mathcal{T}}(t)\right) \tag{9}$$

Proof: Using (5), $\Pi\left(p_{i\in\mathcal{S}\cup\mathcal{T}}(t)\right)$ is as follows

$$\begin{aligned}&\Pi\left(p_{i\in\mathcal{S}\cup\mathcal{T}}(t)\right)\\&=\left(\sum\nolimits_{t\in T}\sum\nolimits_{i\in\mathcal{S}\cup\mathcal{T}}\lambda p_i(t)^+ + \mu p_i(t)^-\right)\\&\quad-\left(\sum\nolimits_{t\in T}\lambda\Big[\sum\nolimits_{i\in\mathcal{S}\cup\mathcal{T}} p_i(t)\Big]^+ + \mu\Big[\sum\nolimits_{i\in\mathcal{S}\cup\mathcal{T}} p_i(t)\Big]^-\right)\end{aligned} \tag{10}$$

Since $\lambda \geq \mu$, we have

$$\begin{aligned}&\lambda\Big[\sum\nolimits_{i\in\mathcal{S}\cup\mathcal{T}} p_i(t)\Big]^+ + \mu\Big[\sum\nolimits_{i\in\mathcal{S}\cup\mathcal{T}} p_i(t)\Big]^- \geq \lambda\Big[\sum\nolimits_{i\in\mathcal{S}} p_i(t)\Big]^+\\&\quad+\lambda\Big[\sum\nolimits_{i\in\mathcal{T}} p_i(t)\Big]^+ + \mu\Big[\sum\nolimits_{i\in\mathcal{S}} p_i(t)\Big]^- + \mu\Big[\sum\nolimits_{i\in\mathcal{T}} p_i(t)\Big]^-\end{aligned} \tag{11}$$

then, we have

$$\begin{aligned}&\left(\sum\nolimits_{t\in T}\sum\nolimits_{i\in\mathcal{S}\cup\mathcal{T}}\lambda p_i(t)^+ + \mu p_i(t)^-\right)\\&\quad-\left(\sum\nolimits_{t\in T}\lambda\Big[\sum\nolimits_{i\in\mathcal{S}\cup\mathcal{T}} p_i(t)\Big]^+ + \mu\Big[\sum\nolimits_{i\in\mathcal{S}\cup\mathcal{T}} p_i(t)\Big]^-\right)\\&\geq\left(\sum\nolimits_{t\in T}\sum\nolimits_{i\in\mathcal{S}}\lambda p_i(t)^+ + \mu p_i(t)^-\right)\\&\quad-\left(\sum\nolimits_{t\in T}\lambda\Big[\sum\nolimits_{i\in\mathcal{S}} p_i(t)\Big]^+ + \mu\Big[\sum\nolimits_{i\in\mathcal{S}} p_i(t)\Big]^-\right)\\&\quad+\left(\sum\nolimits_{t\in T}\sum\nolimits_{i\in\mathcal{T}}\lambda p_i(t)^+ + \mu p_i(t)^-\right)\\&\quad-\left(\sum\nolimits_{t\in T}\lambda\Big[\sum\nolimits_{i\in\mathcal{T}} p_i(t)\Big]^+ + \mu\Big[\sum\nolimits_{i\in\mathcal{T}} p_i(t)\Big]^-\right)\end{aligned} \tag{12}$$

which is clearly equivalent to (9).

In this section, value function of an EC and its properties are discussed. This function and the associated properties are used in the next section to characterize the EC game.

B. ENERGY COMMUNITY GAME

The concept of coalitional games is used here to study prosumers willingness to form a coalition (i.e., EC). Consider a group of N prosumers indexed by $i \in \mathcal{N} := \{1, 2, \ldots, N\}$. Define $\upsilon(\mathcal{S})$ as value function of any coalition $\mathcal{S} \subseteq \mathcal{N}$:

$$\upsilon(\mathcal{S}) = \max_{p_i}\sum\nolimits_{t\in T}\Pi\left(p_{i\in\mathcal{S}}(t)\right) \tag{13}$$

The added value achieved by forming an EC is a reduction in aggregated electricity bill. The added value can be shared among the prosumers without any restriction. This means that the EC game is a game with transferable payoff. As mentioned earlier, a game with transferable payoff can be represented by its set of possible coalitions and value function, i.e., $(2^N, \upsilon)$. Therefore, the EC game is represented by the pair $(2^N, \upsilon)$.

Theorem 4: EC game is super-additive.

Proof: From super-additivity property of function Π established in Lemma 2, for any disjoint pair of coalitions $\mathcal{S} \in 2^N$ and $\mathcal{T} \in 2^N$, we have:

$$\max_{p_i} \sum_{t \in T} \Pi\left(p_{i \in \mathcal{S} \cup \mathcal{T}}(t)\right) \geq \max_{p_i} \sum_{t \in T} \left(\Pi\left(p_{i \in \mathcal{S}}(t)\right) + \Pi\left(p_{i \in \mathcal{T}}(t)\right)\right) \quad (14)$$

since $\mathcal{S}$ and $\mathcal{T}$ are disjoint coalitions, maximizing sum of the two items is equivalent to sum of the maximums as follows:

$$\max_{p_i} \sum_{t \in T} \left(\Pi\left(p_{i \in \mathcal{S}}(t)\right) + \Pi\left(p_{i \in \mathcal{T}}(t)\right)\right) = \max_{p_i} \sum_{t \in T} \Pi\left(p_{i \in \mathcal{S}}(t)\right) + \max_{p_i} \sum_{t \in T} \Pi\left(p_{i \in \mathcal{T}}(t)\right) \quad (15)$$

Putting (15) in (14), we have

$$\max_{p_i} \sum_{t \in T} \Pi\left(p_{i \in \mathcal{S} \cup \mathcal{T}}(t)\right) \geq \max_{p_i} \sum_{t \in T} \Pi\left(p_{i \in \mathcal{S}}(t)\right) + \max_{p_i} \sum_{t \in T} \Pi\left(p_{i \in \mathcal{T}}(t)\right) \quad (16)$$

From value function definition provided in (13), we have:

$$v(\mathcal{S} \cup \mathcal{T}) \geq v(\mathcal{S}) + v(\mathcal{T}) \quad (17)$$

Thus, the game is super-additive.

It is worthwhile to note that super-additivity of the EC game guarantees that prosumers can always decrease their aggregated bill by forming coalitions with other prosumers. The larger the coalition (i.e., EC) the greater reduction in aggregated electricity bill. This can be translated to the fact that grand coalition is the best coalition for any set of prosumers. This however does not guarantee that there exist value sharing mechanisms to make the grand coalition stable. It is also worth pointing out that the game is super-additive if EC formation costs are overlooked. On the other hand, if the costs are significant and cannot be overlooked, it is likely that grand coalition does not become the best option. This is because if the cost imposed by joining a prosumer to an EC exceeds the potential added value it brings, the game is not super-additive anymore and it cannot be claimed that grand coalition is the best coalition.

Theorem 5: EC game is balanced.

Proof: Assume $\alpha : 2^N \rightarrow [0, 1]$ be a balanced collection of weights [18]. Since the game is super-additive and grand coalition has the highest value, we have

$$\sum_{\mathcal{S} \in 2^N} \alpha(\mathcal{S})\, v(\mathcal{S}) \leq \sum_{\mathcal{S} \in 2^N} \alpha(\mathcal{S})\, v(\mathcal{N}) \quad (18)$$

Since $v(\mathcal{N})$ is constant and $\sum_{\mathcal{S} \in 2^N} \alpha(\mathcal{S}) = 1$ holds for any balanced map, we have

$$\sum_{\mathcal{S} \in 2^N} \alpha(\mathcal{S})\, v(\mathcal{S}) \leq v(\mathcal{N}) \quad (19)$$

Thus, the game is balanced.

The direct result of balancedness of the game is that the core is nonempty. This guarantees that there exists at least one value sharing mechanism to make the grand coalition stable. This means if the total payoff is divided among the members using the value sharing mechanism, no member has incentive to leave the grand coalition.

TABLE 1. **A sample EC with three Prosumers: Individual hourly consumption (kWh).**

Player	Hour 1	Hour 2	Hour 3	Hour 4
Prosumer #1	0.6	0.1	-1	0.4
Prosumer #2	1.6	0.7	1.1	1.3
Prosumer #3	0.5	0.8	1.2	1.5

Theorem 6: EC game is not convex.

Proof: Here, a counterexample is presented to show that the EC game is not convex. To do so, consider an EC involving three prosumers, $\mathcal{N} := \{1, 2, 3\}$. The electric energy demand of the prosumers during a 4-hour study horizon is provided in the following table:

In Table 1, negative consumption is equivalent to energy production. In this example, it is assumed that the electricity price for procuring from the network is 16 ¢/kWh. The price for injecting power to the network is 5 ¢/kWh. Using (5), the value associated with each coalition is calculated as follows:

$$v(\{1\}) = v(\{2\}) = v(\{3\}) = 0$$
$$v(\{2, 3\}) = 0$$
$$v(\{1, 2\}) = v(\{1, 3\}) = v(\{1, 2, 3\}) = 11¢$$

Based on the above values, we have

$$v(\{1, 3\}) - v(\{1\}) \geq v(\{1, 2, 3\}) - v(\{1, 2\}),$$

which contradicts the necessary condition for convexity, i.e., (2). Thus, the EC game is not convex. As mentioned earlier, if a coalitional game is not convex, Shapley values do not necessarily provide a stable value sharing mechanism for the grand coalition. Sharing value based on Shapley values, the three prosumers receive a payoff equal to 7.26, 1.87, and 1.87 ¢, respectively. As can be seen, the total share of Prosumers 1 and 2 is 9.13 ¢ in aggregate while the two prosumers have an incentive to leave the grand coalition, form coalition {1,2}, and increase their total share to 11 ¢. Thus, value sharing mechanism based on Shapley values is not in the core for the EC game. This urges the importance of proposing a stabilizing value sharing mechanism for the EC game.

C. STABILIZING VALUE SHARING MECHANISM

There are different approaches to find a stabilizing value sharing mechanism for a balanced game. Among them, nucleolus concept and worst-case excess minimization are more popular [10]. In addition, the analytical formula proposed in [24] can be applied. Since nucleolus-based value sharing is computationally intractable in ECs [10], it is not considered here. The analytical formula is very effective since it provides a stabilizing mechanism without significant computational complexities. However, value sharing mechanism based on the analytical formula allocates the whole cooperation benefit to consumers if the community net consumption is negative.

This may result in dissatisfaction of producers who have invested on local generation facilities. This is in clear contradiction with the global trend toward incentivizing investment on local generation facilities. Since the EC game is not convex, it is likely that it has several stabilizing value sharing mechanisms. So, in the hope of finding a fairer and still stabilizing mechanism, minimizing the worst-case excess is applied here as follows

$$\begin{aligned} &\min_{x} \varepsilon \\ &s.t.\ \upsilon(\mathcal{S}) - \sum\nolimits_{i\in\mathcal{S}} x_i \le \varepsilon \quad \forall \mathcal{S} \in 2^N \\ &\sum\nolimits_{i\in\mathcal{N}} x_i = \upsilon(\mathcal{N}) \end{aligned} \tag{20}$$

In the above problem, x denotes the share of prosumers from the value created by forming an EC including all prosumers. Note that ε must take zero or a negative value at the final solution. Otherwise, there are some prosumers willing to leave the EC to increase their payoff.

In (20), the objective function is optimized subject to a system of linear inequality constraints. The problem is linear and can be solved via several off-the-shelf optimization tools. However, size of the problem grows exponentially as the number of prosumers increases. The computation burden and time grow very fast as the size increases. The huge number of constraints may also make storage requirements challenging. These may lead to difficulties in handling the problem, especially in larger ECs with tens of prosumers.

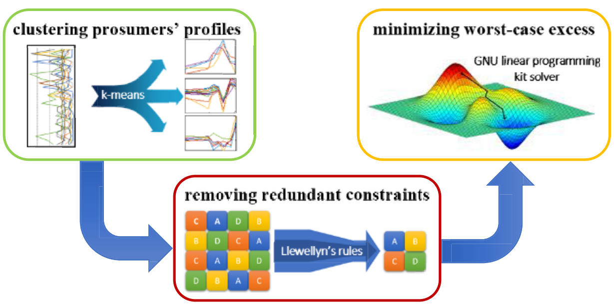

FIGURE 1. **Flowchart of the proposed value sharing approach.**

To alleviate computational burden and time needed to solve the problem, this article proposes to use similarity between prosumers' profiles. Step-by-step of the proposed method is depicted in the flowchart in Fig. 1. According to the flowchart, the first step is to cluster prosumers' profiles into a predefined number of clusters. To do so, this article uses k-means approach as a vector quantization approach. This method minimizes within-cluster variances, thereby putting more similar profiles in the same cluster. Since k-means clustering problem is computationally difficult, heuristic approaches can be applied to solve the clustering problem. The heuristic approaches are usually efficient and quick but may converge to a local optimum. To avoid a local optimum clustering, it is recommended to iterate the process a few times and select the solution with the least achieved within-cluster variances.

The selection of the number of clusters is important. Too many clusters may lead to a computationally intractable problem. On the other hand, a small number of clusters can lead to inaccurate results. In ECs with more similar prosumers like residential ECs, smaller number of clusters is possible without significantly endangering results accuracy. In ECs with prosumers with quite different profiles like industrial and commercial ECs, however, a larger number of clusters is necessary to preserve accuracy. Selecting an appropriate number of clusters is more elaborated later in this section.

Once the prosumers in each cluster and cluster centroids are determined, prosumers' profiles are modified. To do so, the profile of prosumers in a cluster is replaced with the centroid of the cluster. In addition, only one variable is used to indicate the share of prosumers in a cluster. This way, number of variables in the problem is decreased, thereby reducing dimension of the problem.

In the next step, the inequality constraints are investigated to remove redundant constraints. It is worth mentioning that constraints in a problem can be divided into two categories namely necessary constraints and redundant constraints. A necessary constraint cannot be removed from the problem since its removal may change the solution. A redundant constraint can however be removed without changing the solution of the original problem. In other words, considering redundant constraints does not change the feasible region defined by the necessary constraints. To identify redundant constraints, a generalization of Llewellyn's rules [26] is considered here. Consider the following two constraints:

$$\begin{aligned} \alpha_{1,1}x_1 + \alpha_{1,2}x_2 + \cdots + \alpha_{1,n}x_n \ge \beta_1 \\ \alpha_{2,1}x_1 + \alpha_{2,2}x_2 + \cdots + \alpha_{2,n}x_n \ge \beta_2 \end{aligned}$$

The generalization of Llewellyn's rules states that the first constraint is redundant and can be removed if following conditions hold

$$\begin{aligned} &\beta_i \ge 0 \quad \forall i \in \{1,2\} \\ &\alpha_{i,j} \ge 0 \quad \forall i \in \{1,2\}, \quad \forall j \in \{1,2,\ldots,n\} \end{aligned} \tag{21}$$

$$\frac{\beta_1}{\alpha_{1,j}} \ge \frac{\beta_2}{\alpha_{2,j}} \tag{22}$$

Fortunately, the two first conditions always hold in the worst-case excess minimization problem for ECs. In addition, since the EC game is super-additive, $\upsilon(\mathcal{S}) \le \upsilon(\mathcal{T})$ holds if $\mathcal{S} \subseteq \mathcal{T}$. So, the constraint associated with coalition $\mathcal{T}$ is redundant and can be removed if $\mathcal{S} \subseteq \mathcal{T}$ and $\upsilon(\mathcal{S}) = \upsilon(\mathcal{T})$.

It is worth mentioning that comparing values created by EC, i.e., $\upsilon(\mathcal{N})$, before and after applying the method gives a hint about the potential error in the prosumers' shares. The larger difference between the values is, the more erroneous shares for prosumers are achieved. So, it is recommended to calculate the difference for different numbers of clusters first and then select the appropriate number according to the calculated values. This is more elaborated in the next section.

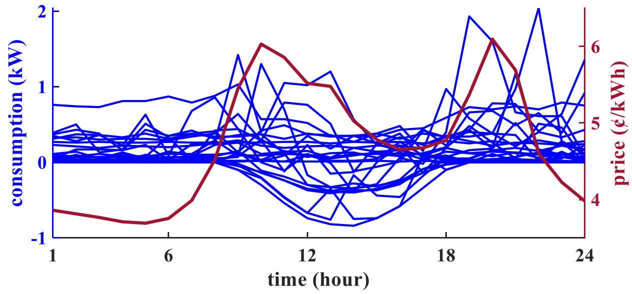

FIGURE 2. Prosumers' electricity consumption and selling price profiles.

IV. SIMULATIONS AND RESULTS

This section studies the EC game and characteristics of the worst-case excess minimization problem for value sharing. It also evaluates performance of the proposed approach in alleviating computational burden and time of the problem. To do so, description of the case under study is followed by comprehensive discussions on numerical results. In the studies, optimization problems are solved via GNU linear programming kit (GLPK) solver in Pyomo Python module using an Intel Core i5 CPU 1.9 GHz, with 16.0 GB of RAM.

A. CASE STUDY

To study properties of the EC game, an apartment building in the southern part of Finland in the metropolitan area is considered. The building has 24 apartments. Approximately, half of the roof area is assigned to solar panels with 15 kW capacity owned by 12 apartments. The hourly data associated with consumers' electricity consumption, solar radiation, and wholesale market price are for March 7, 2018. According to the measurements, the community consumes about 128 kWh during the day. The solar panels generate about 38 kWh in aggregate. The peak demand is 7.22 kW that occurs at 8 in the evening. Solar power is available from 8 in the morning to 5 in the afternoon. The maximum power generation happens at 1 p.m. when 10 apartments have surplus generation. During the day, the community has surplus generation from 1 p.m. to 3 p.m. The community is supplied by Helen Group which consists of both retailer and electric distribution company in the area. According to the historical data, average electricity price was 16.12 ¢ per kWh in the first season in 2018. This price is considered as the price for importing electricity from the network. Helen buys surplus generation based on wholesale market prices which were about 4.7 ¢ per kWh on average. The large gap between the purchasing and selling prices provides a significant incentive for sharing surplus generation inside the EC. It is worth mentioning that energy sharing within an EC located within one property is exempt from tax, VAT, and network tariff in Finland. Fig. 2 depicts prosumers' electricity consumption profiles and hourly prices for selling electricity to the network.

B. NUMERICAL RESULTS

The prosumers' electricity consumption costs are given in Table 2. Needless to mention, negative values represent net revenue of the prosumer from selling electricity to the network. As can be seen in the table, Prosumers 15 and 23 have the highest surplus energy, which is sold to the network, thereby causing negative costs. On the other hand, Prosumers 1, 2, 10, and 19 consume more energy.

TABLE 2. Prosumers' electricity consumption cost [¢].

Prosumer	Cost	Prosumer	Cost	Prosumer	Cost
#1	257.92	#9	-5.23	#17	-8.42
#2	155.88	#10	165.71	#18	149.27
#3	126.13	#11	14.86	#19	171.92
#4	38.53	#12	5.16	#20	102.04
#5	39.14	#13	147.25	#21	80.94
#6	43.04	#14	57.07	#22	38.37
#7	20.93	#15	-26.62	#23	-19.21
#8	18.05	#16	88.50	#24	37.08

TABLE 3. Best coalitions with different numbers of members.

# of members	Members	Payoff [¢]
2	P2, P15	42.69
3	P2, P15, P23	58.45
4	P1, P2, P7, P15	80.72
5	P1, P2, P7, P15, P23	91.24
21	All prosumers except P8, P12, and P21	221.04
22	All prosumers except P8 and P12	223.78
23	All prosumers except P12	224.66
24	All prosumers	225.11

The prosumers may form coalitions to achieve savings in their costs. Since there exist 24 prosumers, coalitions with 2 to 24 members can be imagined. Table 3 presents the best coalitions with different numbers of members. As can be seen, the payoff increases as the number of members grows. This is because the EC game is super-additive. As another observation, the best match is between the prosumer with the highest generation, i.e., Prosumer 15, and one of the prosumers with a high consumption, i.e., Prosumer 2. It is worth noting that though Prosumers 1, 10, and 19 have higher total energy consumptions, but Prosumer 2 consumes more energy during the time Prosumer 15 has surplus generation. According to the results, the grand coalition is the answer to the EC game since it provides the highest payoff. It is worth mentioning that this observation is because purchasing price of electricity is higher than its selling price. If selling price is higher, it is not beneficial for prosumers to form EC and share surplus generation inside the EC since they are able to sell the surplus to the network with higher prices.

Assuming grand coalition as EC, value sharing based on Shapley values is calculated. Although it is proved that value sharing based on Shapley values is not necessarily stabilizing for EC game, it is still valuable to calculate and report the values since value sharing based on Shapley values have been extensively applied in the literature [9], [11], [19]. In addition, the proof was based on a small EC as counterexample. So,

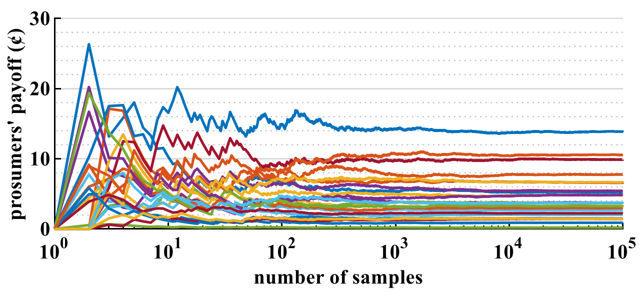

FIGURE 3. Shapley values vs. sample numbers in Monte Carlo simulation.

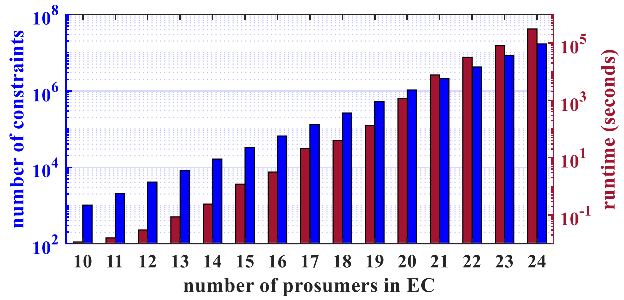

FIGURE 4. Number of constraints and runtime vs. number of prosumers.

TABLE 4. Prosumers' value shares [¢]: Shapley values.

Prosumer	Share	Prosumer	Share	Prosumer	Share
#1	12.23	#9	15.58	#17	15.66
#2	18.29	#10	11.34	#18	11.41
#3	7.33	#11	12.82	#19	7.65
#4	8.81	#12	0.46	#20	8.71
#5	8.65	#13	6.21	#21	5.24
#6	4.77	#14	3.35	#22	3.51
#7	23.26	#15	32.46	#23	24.77
#8	2.09	#16	7.01	#24	3.48

TABLE 5. Prosumers' value shares [¢]: Minimizing the worst-case excess.

Prosumer	Share	Prosumer	Share	Prosumer	Share
#1	11.46	#9	11.64	#17	11.64
#2	21.70	#10	11.81	#18	11.13
#3	3.41	#11	11.64	#19	5.43
#4	8.63	#12	2.41	#20	7.77
#5	4.55	#13	3.95	#21	2.73
#6	2.41	#14	3.11	#22	2.41
#7	21.61	#15	25.52	#23	25.52
#8	2.41	#16	7.77	#24	2.41

it makes sense to demonstrate that in a practical EC too. To calculate Shapley values, the Monte Carlo Simulation approach with 100,000 samples is used [27]. Fig. 3 depicts that the values get almost stable after 10,000 samples.

The results of value sharing based on Shapley values are given in Table 4. As an interesting observation, prosumers with higher generation capability like Prosumers 15 and 23 receive higher shares. According to the results, sum of the shares associated with all prosumers but 8 and 12 is 222.56 ¢ while the prosumers have opportunity to form a 22-member EC to increase their total value to 223.78 ¢ (See Table 3). This means that value sharing based on Shapley values is not stabilizing for the EC game.

As proved earlier, the EC game has stabilizing value shares which can be found via solving (20). The optimization problem is solved for the community, and the achieved shares are given in Table 5. The shares are stabilizing, and no group of prosumers has an incentive to leave the grand coalition.

Although the worst-case excess minimization provides stabilizing shares, this method may become computationally intractable in larger ECs. Fig. 4 depicts the number of constraints and computation time of the problem versus the number of prosumers in the EC. As can be seen, size of the problem and the associated run time exponentially grow as the number of prosumers increases. As can be seen, it takes more than 300 thousand seconds (i.e., about 3.5 days) to solve the problem for the EC with 24 prosumers. The problem for the EC with 24 prosumers has about 16.8 Million constraints.

TABLE 6. Number of redundant constraints (red. cons.) and runtime for different number of clusters.

# of clusters	cluster details	# of red. cons.	runtime (s)
24	{24,1}	---	308294
23	{22,1} {1,2}	4.2 M	158943
22	{20,1} {2,2}	7.4 M	89543
21	{18,1} {3,2}	9.7 M	45741
20	{16,1} {4,2}	11.5 M	45651
19	{15,1} {3,2} {1,3}	13.3 M	8747
18	{14,1} {2,2} {2,3}	14.5 M	5082
17	{14,1} {1,2} {1,3} {1,5}	15.6 M	745
16	{12,1} {2,2} {1,3} {1,5}	15.9 M	512
15	{11,1} {2,2} {1,3} {1,6}	16.3 M	139
14	{10,1} {2,2} {1,3} {1,7}	16.5 M	99
13	{10,1} {1,2} {2,3} {1,7}	16.6 M	17
12	{9,1} {1,3} {1,5} {1,7}	16.7 M	4

To evaluate performance of the proposed approach, it is applied to the EC and the prosumers are clustered in different numbers of clusters. It is crystal clear that using a lower number of clusters leads to more redundant constraints. Table 6 provides the number of redundant constraints and runtime for different numbers of clusters. In the table, {x,y} indicates x clusters with y prosumers. Needless to mention, the first row that has 24 clusters all with 1 prosumer is the base case where prosumers are not clustered. According to the results, the number of redundant constraints increases, and the runtime of the problem decreases as the number of clusters is reduced. As can be seen from the results, using 19 clusters, the run time decreases by more than 97% and the number of constraints is reduced by 5 times.

Although the results demonstrate great performance of prosumer clustering and redundant constraint removal in reducing problem size and runtime, it is likely that clustering prosumers in a small number of clusters leads to inaccurate shares for the prosumers. Table 7 presents accuracy indices of the results for different numbers of clusters. The indices are error in total community payoff (ETCP), average error in

TABLE 7. Accuracy indices of the proposed value sharing mechanism for different number of clusters.

# of clusters	ETCP (¢)	ETCP (%)	AEIS (¢)	MEIS (¢)
23	0	0	0	0.04
22	0	0	0.07	0.83
21	0	0	0.09	0.83
20	0	0	0.13	0.83
19	0.97	0.43	0.29	1.51
18	0.97	0.43	0.32	1.51
17	0.97	0.43	0.53	1.97
16	2.00	0.89	0.79	3.64
15	2.00	0.89	1.00	5.18
14	2.00	0.89	1.19	5.18
13	2.00	0.89	1.13	5.23
12	2.86	1.27	2.08	12.14

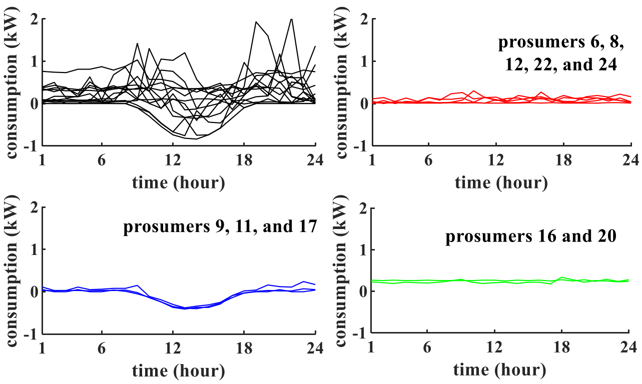

FIGURE 5. Electricity consumption profile of prosumers in different clusters.

individual shares (AEIS), and maximum error in individual shares (MEIS). According to the results, the error in total community payoff is less than 1 ¢ for cases with the number of clusters greater than or equal to 17. The error is less than 1% in all cases with greater than or equal to 13 clusters. AEIS is less than 1 (2) ¢ if the number of clusters is greater than or equal to 16 (13). Finally, MEIS is less than 1 (2) ¢ if the number of clusters is greater than or equal to 20 (17). Therefore, it can be concluded that selecting 20 clusters can lead to almost accurate results and selecting 17 clusters leads to negligible error in EC payoff and prosumers' shares. This negligible error can be overlooked considering the great performance of the proposed approach in reducing problem size and runtime (See Table 6). ETCP, AEIS, and MEIS error indices are positively correlated. This means that ETCP can be considered as an indicator to determine the number of clusters before solving the problem. It is worthwhile to mention that ETCP can be calculated before solving the problem while AEIS and MEIS can be calculated only once the problem is solved.

Assuming 17 clusters, Fig. 5 depicts prosumers' electricity consumption profiles in different clusters. The black profiles belong to prosumers in clusters with one member. As can be seen in the figure, there are 3 clusters with more than one prosumer. AEIS index is equal to 1.40, 1.33, and 0.83 ¢ for the red, blue, and green clusters in the figure. MEIS index is equal to 1.97, 1.51, and 0.83 ¢ for the red, blue, and green clusters in the figure. Considering the number of prosumers in the 3 clusters, it can be concluded that both error indices grow as the number of prosumers in a cluster increase. On the other hand, AEIS and MEIS indices are respectively 0.0003 and 0.0008 ¢ for the remaining prosumers. This means that the shares are accurate for prosumers in clusters with only one member.

V. CONCLUSION

In this paper, a coalitional game was presented for ECs. The game has been proved to be super-additive and balanced but not convex. It has been demonstrated that Shapley values do not provide a stabilizing value sharing mechanism for grand coalition. To find a stabilizing mechanism, minimization of the worst-case excess has been applied. It has been shown that size and runtime of the optimization problem grow dramatically as the number of prosumers in the EC increases. To handle computational complexity of the problem, clustering prosumers based on their electricity consumption profiles and removing redundant constraints have been proposed. To do so, k-means clustering algorithm has been used to cluster prosumers to a predefined number of clusters. Then, generalization of Llewellyn's rules have been applied to remove redundant constraints. Owing to the simulation results, the number of redundant constraints is considerable even if the prosumers are clustered into several clusters. It has been shown that the problem size and runtime can be decreased significantly in the cost of negligible error in share values. The error in the shares is more significant in clusters with more prosumers while the shares are almost accurate for prosumers in clusters with only one prosumer.

ACKNOWLEDGMENT

The authors would like to thank Helen Sähköverkko Oy for providing data associated with an apartment building in the southern part of Finland in the metropolitan area.

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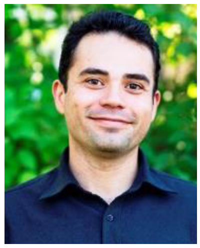

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