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RESEARCH ARTICLE

Cooperative Games Over Blockchain and Smart Contracts for Self-Sufficient Energy Communities

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ABSTRACT The household prosumers' decentralized cooperation and aggregation in energy communities are essential to increase renewable energy penetration and to ensure a successful energy transition. Despite their potential, the prosumers are not motivated to participate in local energy value chains due to the lack of trust and decentralized cooperation models for meeting community welfare and sustainability preferences, most innovation efforts being focused on financial incentives that are anyway very low. In this paper, we propose a solution for prosumers' decentralized coordination in self-sufficient energy communities using cooperative games on top of a blockchain overlay that considers their complementary energy features and flexibility mobilization. The proposed model for community-level local energy balance fits well in circumstances in which there is a strong motivation in the community to prioritize sustainability and environmental concerns and reduce dependence on external energy. We define a governance model to support the decentralized self-organization of prosumers in coalitions for balancing the renewable generation and demand while considering via tokenization factors that go beyond purely economic motivations and foster cooperation and collaboration among the prosumers in the community. Self-enforcing contracts are used to implement the cooperative game model enabling the decentralized management of prosumers' coalitions for optimized tokens-based payoff distribution towards self-sufficiency. The evaluation results show our solution's effectiveness in facilitating the prosumers cooperation in self-sufficient coalitions achieving a minimal difference between the energy consumption and production in the community of approximately 0.01%, with a low transactional time overhead.

INDEX TERMS Blockchain, cooperative games, self-sufficient energy communities, small scale prosumers, renewable energy integration.

I. INTRODUCTION

The need and opportunity for integrating high shares of small-scale prosumers (i.e., smart buildings) at the local level pose challenges not only for the operation of isolated or weakly connected areas but also for the microgrids [1]. In that respect, grid management should closely cooperate and interact within a low latency context with local energy systems to procure flexibility services and to support community-level energy autarchy and autonomy [2], [3]. Tailored measures, technologies and simplified regulations should be considered to support the prosumers towards active participation in the management of energy communities.

The energy community is a group of prosumers who share some common interest or attitudes (e.g., environmental sensibility, local sustainability, etc.) that may be engaged to use

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their flexibility and contribute effectively to local energy sustainability [4]. The prosumers may live within a well-defined geographic boundary such as a district (i.e., local energy community) or not. The prosumers can be aggregated virtually using different criteria, such as their willingness to purchase green energy (i.e., renewable energy cooperatives) [5], [6]. Despite potential of energy communities, the research and operational efforts have focused so far on financial incentives for prosumers to use their flexibility and energy security while neglecting the environmental or the sustainability preferences [7]. Hence small-scale prosumers are not motivated to participate in local energy value chains, and the lack of community cooperation models has slowed down the transition of the European energy systems to lower levels of decarbonization [8].

In this context peer to peer energy trading and coordination models over blockchain overlay may enable the decentralized bottom-up coalition of a larger number of energy prosumers via collective community driven cooperation models [9], [10]. In such models, the prosumers may coordinate to compensate for their surplus or deficit of energy and to optimally exploit their flexibility going beyond the purely profit-driven models towards achieving community-level goals such as local balancing of demand and local production or decreasing the carbon footprint. Moreover, the blockchain can serve not only for the implementation of peer-to-peer energy trading but also to reinforce the prosumers' trust by supporting data sovereignty, tamper-proof registration and sharing of energy metering data, and near real-time audit and settlement [11]. It may also provide the automatic execution of self-enforcing smart contracts among cooperating prosumers to manage energy communities [12]. The prosumers are enabled to keep control of their flexibility assets (i.e., devices, batteries) while trading off among their preferences and community requirements or goals. However limited literature approaches consider the blockchain as an overlay for self-sufficient energy communities.

The proposed model for community-level local balance fits well in circumstances in which there is a strong motivation in the community to prioritize self-sufficiency and reduce dependence on external energy [42], [43]. While buying energy from the grid may offer advantages such as lower costs and better power reliability, there are scenarios where a community might prioritize other factors, such as sustainability and environmental concerns, grid independence or local energy generation. Such energy communities are emerging in Europe to prioritize the reduction of their carbon footprint, promote local renewable energy generation, increase their energy independence, and better withstand energy price disruptions [44], [45]. A community might prioritize the stability in energy costs by relying on local generation and storage, which can provide more predictable long-term energy prices. Also, in this kind of circumstance, the community choice for local energy balance can support the growth of the local economy by creating jobs and running renewable energy projects.

We have considered a cooperative game on top of blockchain and smart contracts to optimize the prosumers' coordination by enabling their decentralized aggregation in community-level self-sufficient coalitions while considering prosumers' energy demand, renewable generation, and flexibility. The cooperative games theory provides effective mechanisms for engaging players in bidding agreements or to form alliances [13]. In these games, players can communicate, negotiate, and make binding agreements, meaning that they commit to certain actions and can be held accountable if they deviate from them [14]. The reward is determined by the collective actions of the coalition (i.e., other players in the alliance), not by individual actions of the players. The cooperative games when used on top of peer-to-peer energy markets may enable the dynamic emergence of prosumers coalitions which collectively may offer increased flexibility while reducing uncertainty [15], [16]. Most approaches in the literature address the creation of coalitions of prosumers on-demand by linking them to energy transactions in a profit-driven manner [17], [18], [19].

In our model, the prosumers' coordination using cooperative games offer an increased capability to capture the beyond financial value drivers and common interests of community members such as local sustainability or carbon footprint. The cooperative games promote collaboration and coordination among prosumers, vital aspect for energy communities to meet their goals and increase the social cohesion of its members [16]. Through their collective efforts, the prosumers can optimize the allocation and utilization of energy resources, resulting in improved community level energy autonomy. Cooperative games offer mechanisms for equitable sharing [46] of community energy resources and payoffs among prosumers alleviating concerns regarding inequality in P2P energy trading and distribution of benefits and costs. Moreover, cooperative games provide the flexibility required to model and analyze different coalition structures [47], which is essential in the context of energy communities with different collaboration rules and sustainability goals. To maximize these benefits, we used Harsanyi's dividend payoff distribution scheme [36] within the cooperative game ensuring the game stability in terms of payoff distribution while not endangering the balance of energy supply with the demand in prosumers coalitions and the energy community.

The novel contributions of the paper are the following:

- A model for energy communities of small-scale prosumers without shared community-level energy assets that may coordinate using their flexibility in day ahead to achieve self-sufficiency.
- A governance model based on cooperative games implemented on top of peer-to-peer energy trading and blockchain to support the decentralized self-organization of prosumers in coalitions to balance the local energy generation and demand.

- Integration of decentralized coalition formation model with self-enforcing smart contracts for optimized payoff distribution and the use of tokens to the beyond financial value of prosumers interactions.

The rest of the paper is organized as follows: section II presents the existing state of the art on using different types of games over peer-to-peer energy trading and the progress beyond, section III shows the cooperative games solution for prosumers coalitions and governance model for community self-sufficiency as well as its decentralized implementation using self-enforcing smart contracts, section IV presents the results obtained for virtual energy community of 30 prosumers using energy profiles provided by energy meters, section V discusses the overall approach while section VI presents conclusions and future work. Table 1 presents the index and variables used throughout the paper.

II. RELATED WORK

In literature the management of peer-to-peer energy trading among energy entities of local energy systems with games theory is mostly addressed using non-cooperative or coalition-based games [13], [16], [19].

In the non-cooperative game applications, the peers which are trading energy compete among them to maximize their own economic benefits without considering the welfare of others [13], [16]. Zhang et al. [20] use non-cooperative games to enable prosumers to compete on energy based on the price showing that a Nash equilibrium can be achieved. However, they consider only limited sources of prosumers' flexible demand and no energy storage. Amin et al. have addressed the problem of energy trading from the perspective of profitability and proposed a change-over mechanism from non-cooperative to cooperative game model [16]. The non-cooperative game-based strategy is used for prosumers with energy demand lower than the generation, while the cooperative game-based strategy is used for prosumers with energy generation surplus. For fair revenue distribution the Shapely method is applied [37]. In [21] game theory is used for P2P energy trading in both islanded and grid-connected mode. The authors propose a four-level goal model to motivate the prosumers to participate and a non-cooperative game to determine the trading price. Jiang et al. propose a two-stage optimization for P2P energy sharing and trading [22]. In the first stage, prosumers will participate in the trading process to obtain the maximization of a social utility function, while in the second stage the optimal payments are obtained using a Nash bargaining model.

The energy trading process and interaction among prosumers is modelled as a Stackelberg game [23] in which the producers are leaders, and the consumers are followers. The prosumers are clustered based on their location and energy trading cost and utility models are defined for renewable systems that consider load demand uncertainty and a social welfare scheme for prosumers. In [24] game theory is used to maximize the usage distributed solar energy. The optimal matching pair of producers - consumer is identified using the Galey–Shapley algorithm, without considering the uncertainties in distributed generation and impact of user behavior. Yap et al. propose a P2P use motivational game theory to maximize the benefices of prosumers and social welfare of the power system utility [25]. The schema is based on an auction mechanism that utilizes priority indices for

TABLE 1. Nomenclature table.

Index and variables	Unit or term
EC	Energy community of prosumers
p	Prosumer
$E_{gen,ren}(t)$	Prosumer's generated renewable energy at the discrete time moment *t*
$E_{s,cap}(t)$	Prosumer's battery storage capacity available for charging/discharging at the discrete time moment *t*
$E_{demand}(t)$	Prosumer's energy demand at the discrete time moment *t*
$E_{load,devices}(t$	Energy consumption of a device of a prosumer at the discrete time moment *t*
$E_{gen,ren}(T)$	Prosumer's generated renewable energy over trading period *T*
$E_{s,cap}(T)$	Prosumer's battery storage capacity available for charging/discharging over trading period *T*
$E_{demand}(T)$	Prosumer's energy demand over trading period *T*
c_f	Cost factor
S	Set of prosumers acting as sellers in P2P energy trading
B	Set of prosumers acting as buyers in P2P energy trading
SS	Set of prosumers acting as self-sufficient prosumers in P2P energy trading
$p_{j,seller}$	Prosumer *j* acting as a seller in P2P energy trading
$p_{k,buyer}$	Prosumer *k* acting as a buyer in P2P energy trading
$p_{m,self-suffici}$	Prosumer *m* acting as a self-sufficient prosumer in P2P energy trading
$E_{surplus}(T)$	Energy surplus of a seller over trading period *T*
$E_{deficit}(T)$	Energy deficit of a buyer over trading period *T*
$E_{EC,balance}(T$	Energy balance within the energy community over trading period *T*
$E_{EC,surpuls}(T$	Energy surplus within the energy community over trading period *T*
$E_{EC,deficit}(T)$	Energy deficit within the energy community over trading period *T*
TX_{offer,p_j}	Transactional offer of a prosumer acting as a seller
TX_{bid,p_k}	Transactional bid of a prosumer acting as a buyer
$U^*_{prediction}(T$	Uncertainty level related to the estimated energy surplus during the period *T*
$payoff$	Prosumer's reward percentage within the coalition
$tokens_{offer}$	Tokens offered to sellers
$tokens_{reward}$	Tokens given as rewards for buyers
ERC721	non-fungible tokens equivalent to the amount of energy offered by a prosumer
LERC20	non-fungible tokens equivalent to the lockable financial payment of a prosumer
$d_v(Co)$	Harsanyi dividend for tokens allocation within coalition Co
Co_{stable,p_j}	Stable coalition of prosumers
$Co_{p-unstable,p}$	Unstable coalition of prosumers
VaR	Value at risk
R_i	Arithmetic return computed based on Historical energy values offered by the seller in the previous transactions
$\check{R}$	Set of return values
α	Confidence level
$\mu(\check{R})$	Mean value from the set of return values
$\check{R}_\alpha$	The worst value from the set of return values

matching the prosumers. A framework based on game theory that integrates a pricing schema for P2P electricity trading in electricity markets is described in [3]. Trading pairs are created based on the preferences of participants to reduce the cost for consumers and increase the revenues for renewable producers. Zheng et al. propose a P2P energy trading model based on game theory for participants connected to a microgrid, the trading process is controlled by an aggregator [26]. Game theory is used to manage the competition among buyers when the demand is greater than the shared energy storage capacity while the equilibrium problem is addressed using a Karush-Kuhn-Tucker optimality condition-based method. A blockchain-based energy trading system in local communities that utilizes two non-cooperative games with dynamic pricing for suppliers is proposed in [10]. The system use a Hyperledger blockchain the demand-response games effectively reducing the net peak load. Zhao et al. propose a non-cooperative game-based method considering multi-region interconnected flexible distribution networks to achieve cost reduction and voltage profile improvement [13]. The operational profits of the soft open points are improved by incorporating spatial active power trading adjustment and temporarily dispatching the energy storage link.

The cooperative games focus on the creation of coalitions energy assets by enforcing cooperative behavior strategies and payoff distribution schemes for coalitions [15], [18], [27]. In [27] the authors propose a set of motivational models for prosumers engagement in peer-to-peer energy trading and canonical coalition game for empowering their cooperation to reduce the cost of electricity and carbon footprint. Similarly, a P2P energy trading schema based on cooperative game for social cooperation among prosumers is proposed in [18]. A utility function is defined to compute the gains of the prosumers considering a mid-market rate trading schema and the battery degradation cost. Long et al. use game theory and Shapley value for P2P energy trading process by considering energy optimality and price fairness for prosumers [28]. The financial benefits for the coalitions created are determined using the prosumers' energy values and the Shapley value is computed for fair sharing. In [29] considers the energy trading among prosumers in a community having a shared energy storage facility aiming to maximize the prosumers profits and revenues from using the storage. A Stackelberg game model is used with the storage as the leader of the game, the consumers are the followers and a utility function considering prosumers' preferences and comfort. Ali et al. [30] identify the optimum sizes of players a cooperative game theory based on particle swarm optimization. The approach used both on peer to the grid and peer-to-peer trading schemes using weather forecast data and load profiles provided by the Australian electricity market. Malik et al use cooperative game theory considering geographic location, maximum energy demand and generation and pricing mechanism aiming to maximize the social welfare of a local energy community [15]. The peers decide to participate in the trading process by charging or discharging the community shared energy storage. A P2P energy trading schema between renewable powered microgrids based on bargaining cooperative game is proposed in [4]. Prosumers can trade among each other or with the power grid to improve the community's benefits as well as their benefits. The fractional hedonic game that aims to improve the participation rate of prosumers in the trading process and increase their social welfare [31]. The utility of a player is computed as the average of the utilities of the other players in the coalition. Player preferences are also considered when creating coalitions.

Wang et al. use cooperative game theory to facilitate peer-to-peer trading of electricity and heat [14]. Participants can optimize their net benefits by choosing the coalition to join, deciding whether to act as a seller or buyer of electricity and/or heat and determining the quantities to be traded. A model for an energy-sharing community that combines blockchain, cooperative game, and a two-level incentive mechanism is proposed in [32]. It uses a modified internal pricing scheme based on the proof-of-credit consensus and cooperative game theory to motivate individuals to follow renewable energy using time-of-use pricing. Cooperative game theory and Particle Swarm Optimization are used to implement a peer-to-peer energy trading system for clustered microgrids [33]. The cooperative game is employed at each microgrid level to promote fairness and efficiency and alleviate the impact of the intermittent nature of renewable resources. A bi-level energy management framework to facilitate peer-to-peer energy trading among multiple prosumers in the retail market is presented in [34]. A cooperative Stackelberg game model is used to formulate the interaction process, where a retailer serves as the leader in determining price discrimination for various prosumers to maximize social welfare. The prosumers act as followers and cooperate through a general Nash bargaining scheme. A stochastic programming approach with Conditional Value at Risk is used to address the uncertainty of renewable energy. In their work, Saeed et al. [19] propose a central energy management system for buildings that aims to optimize energy sharing, reduce energy waste, and maintain the balance between generation and demand. The system employs coalition game theory, utilizing the Shapley value to allocate surplus energy to deficient buildings. A peer-to-peer trading platform on a consortium blockchain using evolutionary game theory is proposed in [9]. The game model and an equilibrium-solving algorithm allow for determining the most advantageous transaction price and quantity. Finally, Lee et al. use three games to determine the optimal trading price and energy amount: an evolutionary game between buyers, non-cooperative games between sellers, and Stackelberg games between sellers and buyers [35]. The community manager indirectly provides information to evaluate the sellers, and a utility value based on an increase/decrease ratio.

Most of the current approaches analyzed above consider the game theory for the competition of prosumers using price-driven solutions over peer-to-peer energy trading. Remarkably few are considering the case of blockchain overlay as support for the decentralized organization of small-scale energy prosumers in energy communities without any shared energy storage resources while considering tokenization for capturing beyond financial values in cooperation. None to our knowledge consider the case of self-sufficient energy communities in which prosumers cooperate using smart contracts to achieve a local balance between local renewable generation and energy demand and coordinate collective energy flexibility to minimize the exchanges with the grid.

III. PROSUMERS COOPERATION OVER BLOCKCHAIN

In this section, we describe the blockchain infrastructure and its roles and the governance model based on cooperative games to support the management of self-sufficient energy communities of prosumers. The integration between the blockchain overlay, peer-to-peer energy trading and coalitions management is done using smart contracts that enable the decentralized cooperation of prosumers.

A. BLOCKCHAIN INFRASTRUCTURE AND ROLE

The blockchain is used as a decentralized overlay infrastructure on top of the local energy grid, offering a secure and reliable network that connects prosumers in the community and enables them to engage in peer-to-peer energy transactions. The energy transactions made among prosumers are registered in a distributed ledger which is setup and shared at the community level, the transactions being traceable and immutable.

In our cooperative game theory approach, operations such as order registration, initiation, and evaluation of coalitions stability, as well as payment and energy exchanges, are registered via the blockchain ledger. The transactions initiated by prosumers belonging to the community are propagated in the community network, grouped in blocks, and mined. After adding blocks to the blockchain network is ensured that the transactions have been previously validated and are now securely registered due to the hashing mechanism and will not be modified or altered. Also, the traceability and transparency of blockchain transactions improves prosumers' trust and enable them to be involved in energy community management.

Smart contracts are pieces of code that once deployed on blockchain can't be modified or altered. They enable implementation of self-enforcing algorithms that are executed through blockchain transactions while also keeping data records. By using smart contracts blockchain transactions are associated with some predefined actions that are triggered if the specified preconditions are met. The smart contract code is executed on blockchain in a secure manner. In our solution, the prosumers will deploy smart contracts that store in its state information about their assets and enable the automated registration of prosumer-monitored energy data. The prosumers can send transactions using smart contracts to participate in the energy community management, such as defining buy or sell orders and initiating coalitions. A smart contract for cooperative trading is defined to keep track of the created coalitions. When the prosumers decide to place a sell offer with their energy surplus, they initiate a transaction which automatically triggers the deployment of such smart contract. Similarly, if the prosumers decide based on their energy deficit to place bids, the register order transaction triggers a function in the cooperative trading contract that enforces the initial phase of the game theory algorithm which is the coalition selection process. After the bidding phase, the prosumers that initiated coalitions can make the transaction that enforces the accept bids phase of the algorithm.

We have defined two types of tokens specifically designed to facilitate energy transactions and financial settlements between prosumers. The Lockable ERC20 (LERC20) token [38] is implemented as an extension of the fungible ERC20 [39] standard with new functionality added to lock and unlock trading operations. The LERC20 tokens are used for modeling the payments and payoff for prosumers. The prosumers can transfer the tokens, give allowance to another address, and lock or unlock tokens in transactions. The locking mechanism prevents the owner from spending the tokens committed in transactions directly. Instead, a designated third party is entrusted with the authority and responsibility to unlock and transfer the tokens when necessary. The tokens are locked-in for several blocks, and only after this predetermined period has elapsed, they can be unlocked and transferred. The second type of token is ERC721 [40], a non-fungible one adapted to digitize and represent the transacted energy. They are minted by the smart contracts when a sell order is registered, and when a bid offer is accepted in a coalition they are transferred to the buyer. ERC721 contains metadata about the energy, such as energy quantity, the start time, and end time for the represented energy quantity. It has functionality for transferring tokens between prosumers as well as allowances.

The choice between private and public blockchains depends on the specific needs and requirements of the energy community. Factors such as trust, scalability, privacy, governance, and regulatory compliance should be considered. Public blockchains are suitable for energy communities that prioritize democratization. Transparency is higher in such blockchains, reinforcing the prosumers' trust in community management and the government is fully decentralized without an authority or third party that manages the chain. Nevertheless, the cost of transactions can be significantly higher in such blockchain making them not feasible for small communities of prosumers.

Private blockchains are suitable for energy communities that require controlled access, trusted participants, and confidentiality, such as collaborations among various stakeholders in the energy supply chain. The private blockchain has restricted access, a central authority granting permissions and offers possibilities for configuration following the energy community rules. In private blockchains privacy and confidentiality can be provided according to the specific community level agreements, and access to some types of transactions can be restricted. For a public blockchain some aspects must be considered regarding prosumer privacy, scalability, and transactions costs. Whilst in a private network, the prosumers participate in an enclosed environment with accounts that are verified and received permission to participate, in a public network anyone can create an account and implicitly view all transaction history. The address of an account is not directly connected to the user and that ensures a degree of confidentiality, but there remain some concerns related to the privacy of user data.

Related to cost and gas consumption in private configurations the gas consumption limit for a transaction can be configured, whilst in the public networks it is established through the consensus mechanism. Given the complexity of the transactions involved in the game theory approach and the gas consumptions, the transaction fees can be very high, and this aspect is important when considering a public blockchain setup. Thus, a compromise should be made by reducing the algorithm complexity and implicitly the transaction fees by moving some of the algorithm's steps off chain while also keeping the advantages offered by blockchain technology. In this case, the data to be stored in smart contracts could also be reduced by keeping only the information that is necessary for the parts of the algorithm that are executed on chain.

After weighing the pros and cons, a private blockchain network established at the community level fits better with our self-sufficiency model. It allows for properly considering the community's rules and objectives, while also addressing the transactional and operational costs that might be unsustainable for prosumers on a public network.

B. COOPERATIVE GAMES FOR SELF-SUFFICIENT ENERGY COMMUNITIES

We model the energy community as a set of N prosumers, sharing a common objective and able exchange information and transact energy flexibility using the blockchain infrastructure.

A prosumer is a household that has on premise energy assets for generation, consumption, and storage of energy. The assets are placed behind a smart meter that can measure the energy taken from the microgrid and the energy injected in the microgrid. From the energy community perspective, a prosumer is modelled in each discrete time instance t of 1 hour:

$$p = \left(E_{gen,ren}(t), E_{s,cap}(t), E_{demand}(t)\right) \tag{1}$$

In (1) $E_{gen,ren}\,(t)$ denotes the renewable energy generated by the prosumer, $E_{s,cap}(t)$ symbolizes the prosumer's battery storage capacity available for charging or discharging and $E_{demand}(t)$ marks the energy demand of the prosumer corelated with the energy consumption of the devices available on its premises:

$$E_{demand}\,(t) = \sum\nolimits_{devices \in P} E_{load\,,devices}(t) \tag{2}$$

The energy demand of a prosumer can be flexible and can be modified in time by shifting the flexible loads , $E_{flex}(t)$), resulted from modifications in the usage patterns of the available devices that consume energy. Thus, the energy demand can increase or decrease at t as:

$$E_{demand}\,(t) = E_{demand}\,(t) \pm E_{flex}(t) \tag{3}$$

Our model aims to achieve an energy balance between the aggregated production and energy demand of the prosumers from the community in day ahead interval T (i.e., 24 hours ahead). Considering its energy balance for the next day, a prosumer can be in one of the following states: energy seller, energy buyer and energy self-sufficient.

We denote with S the set of prosumers acting as energy sellers in the community as:

$$S = \{p_{j,seller} | p_j \in EC \wedge E_{demand}\,(T) < E_{s,cap}\,(T) + E_{gen,ren}\,(T)\,, j \in \{1, ..J\}\} \tag{4}$$

A seller has an energy surplus $E_{surplus}\,(T)$ meaning an amount of energy production that is not covered by its energy demand :

$$E_{surplus}\,(T) = E_{gen,ren}\,(T) - E_{demand}\,(T) \tag{5}$$

The set of buyers are marked with B and is defined as:

$$B = \{p_{k,buyer} | p_k \in EC \wedge E_{demand}\,(T) > E_{s,cap}\,(T) + E_{gen,ren}\,(T)\,, k \in \{1, ..K\}\} \tag{6}$$

A buyer has a deficit in energy generation $E_{deficit}\,(T)$, meaning that its energy demand is not covered by its generation:

$$E_{deficit}\,(T) = |E_{s,cap}\,(T) + E_{gen,ren}\,(T) - E_{demand}\,(T)\,| \tag{7}$$

The prosumers that are self-sufficient are in a balanced state considering their demand and energy generation:

$$SS = \{p_{m,self-sufficient} | p_m \in EC \wedge E_{demand}\,(T) \cong E_{s,cap}\,(T) + E_{gen,ren}\,(T)\,, m \in \{1, ..M\} \tag{8}$$

The prosumers in self-sufficient state will they have neither a deficit nor a surplus:

$$E_{self-sufficient} = E_{demand}\,(T) - E_{gen,ren}\,(T) \cong 0 \tag{9}$$

The union of all distinct types of prosumers comprises the entire set of prosumers within the community:

$$N = |S| + |B| + |SS| \tag{10}$$

As the change in the usage patterns for utilizing the available flexibility may affect the comfort level of the residents and may interfere with their goals, it will be quantified as a cost factor. The changing factor in using flexibility is modelled based on the energy state of the prosumer and potential transitions due to flexibility utilization as:

$$c_f = \begin{cases} \geq 1 \; if p_i \in B \rightarrow BS \rightarrow S \\ (0, 0.5) if p_i \in B \vee S \rightarrow SS \\ [0.51)\,, if \;\, p_i \in SS \rightarrow B \vee S \end{cases} \tag{11}$$

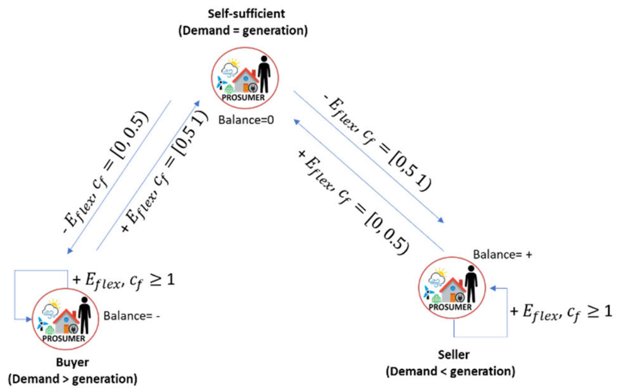

FIGURE 1. **Energy state changes of energy prosumers.**

Therefore, if the prosumer is an energy seller or buyer will have a high cost in utilizing their flexibility in the sense of increasing their energy dependence and remaining in the same energy state. The energy seller or buyer will have a small cost factor in the interval (0, 0.5) for modifying its demand patterns to reach a self-sufficient state as it is directly interested in covering its surplus or deficit using its flexibility to reduce their energy dependence (see Figure 1). The self-sufficient prosumers have a higher cost factor in the interval [0.5, 1) for using their flexibility as they will need to be more substantially motivated to get out from the balance energy state to consume or provide more energy. Moreover, in the payoff distribution the cost factor is multiplied with the amount of energy flexibility provided to the coalition thus rewarding more the prosumers that deliver more flexibility.

To estimate for each prosumer the renewable energy production and consumption patterns and the flexibility amount available in day ahead the proposed model uses prediction techniques. As the energy exchanges are happening in the day ahead it is possible that some prosumers change their role or deliver a smaller amount of energy flexibility compared to the estimated ones. Thus, we have modeled the role-changing for prosumers considering the uncertainties in renewable energy by incorporating a rule-based system to determine the appropriate roles of prosumers using closer to real-time conditions and preferences of the prosumer. Additionally, specific tolerated variations are defined to indicate when a role change is necessary based on the prediction model uncertainty. Considering the acceptable ranges for variation, if the renewable energy generation is lower than the prosumer's consumption needs could trigger a role change from a seller to a buyer or if the energy generation is higher than the prosumer's consumption, it may switch to self-sufficient.

We use cooperative games for creating coalitions of prosumers in energy community with the goal of balancing the energy generation and demand. The common goal of the prosumers is the operate in a self-sufficient manner fully powered by the renewable energy produced inside the community and with minimal energy exchanges with the main grid:

$$E_{EC,balance}\,(T) = E_{EC,surpuls}\,(T) - E_{EC,deficit}\,(T) \cong 0 \tag{12}$$

The achieve this goal each prosumer that are energy sellers will try to form coalitions of prosumers to balance its extra generation with the help of energy buyers that have extra demand or by convincing the self-sufficient prosumers to transit in the consumption state. For this it will use the blockchain tamperproof data sharing features and will publish a transactional offer on the chain that is willing to provide the energy surplus to other prosumers interested.

$$Tx_{offer,p_j} = (p_j, E_{surplus}\,(T) \pm U^*_{prediction}\,(T)\,, payoff) \tag{13}$$

The amount of energy to be traded by the seller for T interval is established considering a degree of uncertainty associated with the estimated surplus for the day ahead interval ($U^*_{prediction}\,(T)$). The *payoff* defines the way in which the rewards are being distributed to prosumers considering their type (i.e., buyers and self-sufficient) in the coalition. The energy surplus offered to other prosumers of the energy community is digitized in blockchain using a combination of ERC721 and LERC20. They are minted in an amount equivalent to the energy offered by the prosumer:

$$tokens_{offer} = \left(E_{surplus}\,(T) \pm U^*_{prediction}(T)\right)^{ERC721}_{LERC20} \tag{14}$$

ERC721 is used to represent the energy as a non-fungible token strictly associated with the prosumer that had generated the energy, while LERC20 is used to offer support for tokens distribution and payments. The seller will prefer to aggregate enough energy demand such that its energy surplus is balanced over the amount tokens left in its wallet.

The aim is to balance the production and consumption for the next interval T therefore the energy surplus of the prosumer is predicted. To determine the uncertainty $U^*_{prediction}$ a statistical measure such as value at risk, *VaR* is used. It measures the potential financial loss of a seller due to an inaccurate prediction of the energy committed to being sold in an offer with a confidence level that represents the certainty associated with the estimation (i.e., a low confidence level implying more uncertainty of the prediction). The accurate prediction of the amount of energy to be delivered is important because failing to meet the committed energy amount in the day ahead may lead to financial penalties or reputational damage. Thus, the seller uses the variability at risk to assess the risks involved in the offer and make informed decisions about participating in the market. Historical values regarding the amount of the energy offered by the seller in the previous transactions can be used to determine the arithmetic returns as:

$$R_i = \frac{E^{i+1}_{surplus}\,(T) - E^{i}_{surplus}\,(T)}{E^{i}_{surplus}\,(T)}, 0 \leq i \leq m \tag{15}$$

where m is the number past values considered, $0 \leq i \leq m$, and R_i is the arithmetic return over the period $[i, i+1]$. Therefore, the result of this step is a set of return values R of size $m-1$:

$$\check{R} = \{R_i | R_i \leq R_j \in R \tag{16}$$

Then, the value $\check{R}_\alpha$ corresponding to the confidence level α is determined from the sorted set of returns and the VaR at the confidence level α is computed as:

$$VaR = \mu\left(\check{R}\right) - \check{R}_\alpha \tag{17}$$

where $\mu\left(\check{R}\right)$ is the mean return of the determined set, and $\check{R}_\alpha$ represents the worst return from the set.

The smart contracts associated with the buyers will be executed in response to the offers shared into the blockchain network. To determine if it will respond to the offer the smart contract of a buyer will evaluate if it is able to provide partially the required energy and the associated reward that it will obtain:

$$tokens_{reward}\left(E_{deficit}(T), Tx_{offer,p_j}.payoff\right) > c_f * (E_{deficit}(T) + E_{flex}(T)) \tag{18}$$

A buyer is motivated to participate in a coalition only if the token distribution scheme applied by the seller energy offer generates a reward that is higher than its cost associated with the use of flexibility. They will publish on the blockchain transactional orders containing the energy deficit and the amount of flexibility that can be used together with their cost factor c_f and the offer to which they are reacting:

$$Tx_{bid,p_k} = (p_k, E_{deficit}(T), E_{flex}(T), c_f, Tx_{offer,p_j}) \tag{19}$$

As the transactions are being disseminated on the blockchain network the smart contracts of the seller is executed each time a bid is received to determine the payoff for accepting the sellers in the coalition. As the solution is implemented on the blockchain we need so distributed way of determining the payoff considering the tokens distribution. When a buyer is accepted in a coalition, a fraction of the seller's tokens is transferred to the buyer according to the token distribution schema from the seller's offer. The tokens distribution function $d_v(Co)$ for the coalition Co is computed using the Harsanyi dividend formula [36]:

$$d_v(Co) = tokens_{reward}\left(Tx_{offer,p_j}\right) - \sum_{c=1}^{C} tokens_{distributed}(Tx_{bid,p_c}) \tag{20}$$

where $tokens_{distributed}$ is the number of tokens assigned to each of the prosumer p_c that is becoming member of the coalition Co.

If the buyer is not accepted in the coalition, it will be notified, and may participate in a second stage for building stable coalitions. The coalitions with tokens distribution function d_v value greater than zero and balance between the energy offer and the sum of energy bids will be considered stable:

$$Co_{stable,p_j} \leftrightarrow d_v(Co) > 0 \& Tx_{offer,p_j} \cong \sum_{c=1}^{C} Tx_{bid,p_c} \tag{21}$$

The coalitions with tokens distribution function d_v value greater than zero but without sufficient energy bids aggregated to cover the seller surplus are considered unstable:

$$Co_{p-unstable,p_j} \leftrightarrow d_v(Co) > 0 \& Tx_{offer,p_j} > \sum_{c=1}^{C} Tx_{bid,p_c} \tag{22}$$

In the second stage of the process will participate only the unstable coalitions and the buyers that were rejected in the first stage. The unstable coalitions are destroyed and the remaining surplus of energy from them is aggregated to a single offer:

$$Tx_{offer,Co_{p-stable}} = \sum (Tx_{offer,p_j} - \sum_{c=1}^{C} Tx_{bid,p_c}) \tag{23}$$

The tokens associated with the surplus will be aggregated as well and the payoff value will be set to a minimum of all the payoff of the sellers. The buyers rejected in the first stage will send the bids and will be accepted based on trust, amount of energy and cost factor. Balance will be achieved for the sellers of their surplus of renewable being consumed locally. In case there are buyers rejected even in this stage and there is no seller for them they will buy the energy from the main grid. The process of creating stable coalitions is done using the smart contracts presented in the next section.

C. SMART CONTRACTS FOR MANAGING COALITIONS

The cooperative game model was implemented utilizing smart contracts deployed on a private network setup of Ethereum enabling prosumers to manage actions based on their state for constructing self-sufficient coalitions.

The prosumers with surplus renewable energy will register sell orders through Prosumer Contract and initiate the construction of coalitions to aggregate enough energy demand to reach a balanced energy state (see Figure 2). The LERC20 tokens represent the payoff, and ERC721 tokens are minted to represent the energy surplus of the prosumer. They use the Build Coalition smart contract to publish sell orders on the blockchain containing the total quantity of tokens that they may distribute. As the Build Coalition smart contract is deployed and the selling offer is stored in the contract state, the coalition state is set to ACCEPTING_BIDS. The amount of reward tokens is set to the energy surplus defined by the offer multiplied by the payoff percentage for the self-sufficient prosumers. As their payoff is higher than the one of all the other prosumers in a deficit state, it will ensure that the tokens of the coalition provided by the seller are enough to cover the buyers' needs. Then, buyers can register their bids, and they can select through the Cooperative Trading Session contract the coalition that satisfies their energy deficit and has the best payoff. After all prosumers register their orders,

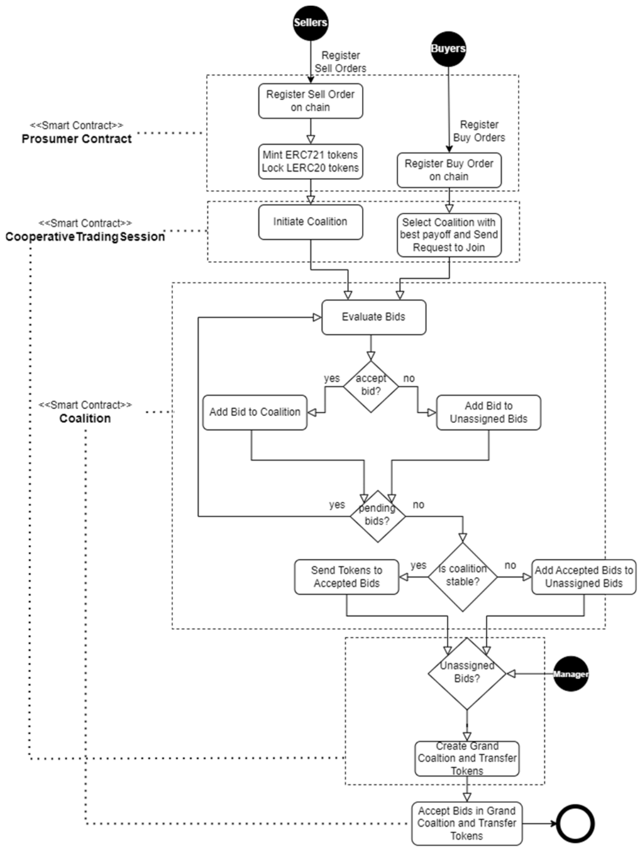

FIGURE 2. Flow diagram for functions and smart contracts interaction.

each coalition evaluates and accepts the bids that satisfy their constraints.

The bids that are not accepted in the coalition are added to the unassigned bids array that will enter the second stage. After all bids are evaluated, if the coalition state is stable, the tokens representing the energy surplus and payoff are distributed to the accepted buyers. Otherwise, all the coalition accepted bids are added to the unassigned bids array. In the second stage, the manager requests the initiation of the grand coalition through the Cooperative Trading Session contract with the aggregated coalitions that were not in a stable state. Similarly with the first step, the remaining unassigned bids are evaluated and the ones that meet the constraints are accepted in the grand coalition determining the state of the grand coalition. .

A prosumer in an energy deficit state can request to join an initiated coalition using the function presented in Algorithm 1 that defines the Build Coalition contract. The method inputs are the address of the caller contract and the prosumer's buy order. If the coalition state is ACCEPTING_BIDS (see line 5), the buy order is added at the end of the pending bids array (line 6-7). The array containing all the pending bids of a coalition is sorted by their flexibility usage cost (lines 8-13). The index and associated tokens are kept in the corresponding mappings (lines 15 and 16), while the cost of the buy order is computed by multiplying the energy flexibility with the changing factor for the prosumer state.

Algorithm 1 Smart Contract BuildCoalition for prosumers request to join an initiated coalition as a buyer

```
1:  Function requestAddBid
2:    Input: msg.sender, order
3:    Output: -
4:    Begin:
5:      Requires msg.sender == owner and coalitionState
          ==ACCEPTING_BIDS
6:      idx ← pendingBids.length
7:      pendingBids.push(order)
8:      For i ← pendingBids.length - 2, 0
9:        IfcomputeBidAssociatedCost(pendingBids[i]) >
          computeBidAssociatedCost(pendingBids[i+1])
10:         pendingBidToIdx[pendingBids[i].id] + = 1
11:         pendingBids[i] ↔ pendingBids[i+1]
12:         idx - =1
13:       End If
14:     End For
15:     pendingBidToIdx[order.id] ← idx
16:     pendingBidAssociatedTokens[order.id] =
          order.energyDeficit
17: END
```

The seller prosumer that initiated the coalition evaluates all the buy orders submitted by prosumers stored in the pending bids array and will accept the ones that satisfy the coalition stability constraints (see *Algorithm 2*). The coalition will determine the difference between the remaining quantity of energy surplus and the buy orders received (lines 7-31). At each iteration, if the difference is still positive no additional flexibility is needed from that buyer prosumer, and the iteration will continue. If the difference is negative and the remaining energy surplus in the coalition is smaller than the available flexibility of the currently considered prosumer additional flexibility from its side will be requested (line 9). The smart contract determines the additional flexibility for the bids with prosumers that have energy deficit, the tokens are increased proportional, and the token distribution function for the coalition is updated (lines 11-13) and must remain positive. If the constraints are met the buy order is accepted in the coalition (lines 15-19). If the prosumer is in a self-sufficient state, flexibility is used to increase its consumption to complete the remaining energy surplus (23-36). The state of the coalition is evaluated using the buy orders that satisfy the constraints stored in the coalition registry. If the energy surplus from the sell offer is not equaled by the total energy deficit of all the accepted buy orders, the coalition is only PARTIALY_STABLE otherwise it is STABLE (line 38). The pending buy orders that are not accepted will enter a second stage of the game with coalitions partially stable.

To keep track during a transactive session of all coalitions initiated by the prosumers and all the buy orders submitted by the prosumers, we have defined a Cooperative Trading Session smart contract (see *Algorithm 3*). It specifies the transactive session interval to construct coalitions and store the build coalition contracts, the coalitions that were partially stable after the first stage and the buy orders that were not accepted in the first stage (lines 2-4). It also keeps mappings

Algorithm 2 Smart Contract BuildCoalition to determine stable coalitions by evaluating the prosumers bids

```
1: Function evaluateAndAcceptBids
2:     Input: msg.sender
3:     Output: coalitionRegistry //buy off. accepted in coalition
4:     Begin:
5:       Requires msg.sender == owner and coalitionState ==
           ACCEPTING_BIDS
6:       offerQuantity ← sellOffer.energySurplus
7:       For i ← 0, pendingBids.length
8:         If pendingBids[i].state == BUYER
9:           DIFF ← offerQuantity – pendingBids[i].energyDeficit
10:          IFDIFF >= 0 OR (- DIFF) <= pendingBids[i].energyFlexibility
11:              flexibilityUsed ← max(0, -DIFF)
12:              pendingBidAssociatedTokens[pendingBids[i].id]
         + = flexibilityUsed
13:              tempDvC ← tokenDistribution(i)
14:              If tempDvC > 0
15:                offerQuantity
         -= (pendingBids[i].energyDeficit - flexibilityUsed)
16:                dvC ← tempDvC
17:                coalitionRegistry.push(pendingBids[i])
18:                delete pendingBids[i]
19:                i - =1
20:                acceptedEnergy[pendingBids[i].id] ←
         pendingBids[i].energyDeficit - flexibilityUsed
21:              End If
22:          End If
23:        Else
24:          flexibilityUsed ← (offerQuantity >=
         pendingBids[i].energyFlexibility) ?
25:                pendingBids[i].energyFlexibility : offerQuantity
26:          pendingBidAssociatedTokens[orderId] + = flexibilityUsed
27:            tempDvC ← tokenDistribution(i)
28:            If tempDvC >= 0
29:              offerQuantity -= flexibilityUsed
30:              dvC ← tempDvC
31:              coalitionRegistry.push(pendingBids[i])
32:              delete pendingBids[i]
33:              i - =1
34:              acceptedEnergy[pendingBids[i].id] ←
         flexibilityUsed
35:            END If
36:          End If
37: End For
38:       coalitionState ← offerQuantity = 0 ? STABLE : PARTIALLY_STABLE
39:       Return coalitionRegistry
40: END
```

between the seller prosumers and their offer orders and initiated coalitions, as well as between buyer prosumers and their buy orders (lines 5-7). The prosumers that act as sellers will register their sell offers using the function provided by smart contract, and a new build coalition contract is deployed (line 14). The coalition is added to the array, and the prosumer contract address is linked with the sell offer and the coalition initiated (lines 16-17). Finally, an event is emitted with the block timestamp and the address of coalition created (line 18).

The buyers and self-sufficient prosumers can request to register the buy orders using the function presented in *Algorithm 4*. They select the coalition with the highest reward that satisfies their energy deficit with the constraint that the energy surplus of the coalition is higher than the sum of energy deficit and flexibility of buy order (line 10). The token reward is computed using the token distribution schema established by the seller that initiated the coalition and

Algorithm 3 Smart Contract CooperativeTradingSession for registration of prosumer's sell offers

```
1:  State:
2:    uint timeInterval
3:    Coalition [] coalitions, partiallyStableCoalitions
4:    GridOperableLibrary.BuyOrderCooperative[]
          unassignedBids
5:    mapping(address => GridOperableLibrary SellOffer-
  Cooperative) sellOffers
6:    mapping(address => GridOperableLibrary BuyOrder-
  Cooperative) buyOrders
7:    mapping(address => GridOperableLibrary SellOffer-
  Cooperative) sellerToCoalition
8:    address owner, _lerc20Address
9:  Function registerSellOffer
10:   Input: msg.sender, sellOffer, block.timestamp
11:   Output: -
12:   Begin:
13:     Requires msg.sender == owner
14:     coalition ←new Coalition(sellOrder)
15:     coalitionAddresses.push(coalition)
16:     sellOffers[sellOffer.sellerEfe] ←sellOffer
17:     sellerToCoalition[sellOffer.sellerEfe] ←
          address( coalition)
18:     Emit RegisterSellOffer(sellOrder, block.timestamp,
          address( coalition))
19: END
```

considering the current state, buyer's energy deficit and energy flexibility (line 11). Only the coalitions with a higher token reward than the cost associated with the flexibility usage are selected (line 12). The buy order is saved in the defined mapping at the address of the prosumer (lines 20-21) and a register buy order event is emitted with the timestamp of the current block and the address of the coalition (lines 22-23).

After the first stage ends, a new grand coalition is created by grouping the sell offers of PARTIALLY_STABLE coalitions using the function from *Algorithm 5*. The offer is initialized with the seller address and for each partially stable coalition, the energy surplus and payoffs are added to sell offer (lines 7-11). The payoff of the new sell offer is computed as an average between the payoffs of all the remaining coalitions (lines 12 and 13). The grand coalition is created by joining the sell offers (line 14) of all unstable coalitions and remaining prosumers with energy surplus (lines 15-18). The tokens corresponding to their energy surplus are transferred from the partially stable coalition that will be destroyed to the newly created grand coalition (line 17). Then, the coalition reward is computed for each bid order that was added in the first stage to the unassigned bids array. The changing factor is divided, and the bid orders participate in this stage with lower flexibility associated costs (line 21-23). If their constraints are met, they send a request to join the grand coalition (lines 20-28). In this case, the coalition keeps two different arrays for the pending bids, one for the bids that have energy deficit corresponding to buyers, and one for the bids corresponding to self-sufficient prosumers. They are kept ordered by their energy deficit are evaluated and added to

Algorithm 4 Smart Contract CooperativeTradingSession registration of prosumer's buy orders

```
Function registerBuyOrder
    Input: msg.sender, buyOrder, block.timestamp
    Output: address of the selected coalition
    Begin:
      Requires msg.sender == owner
      selectedCoalitionIdx ←0
      maxReward ←0
      _cf ← buyOrder.state == BUYER ?
        buyOrder.cf.SB_SS: buyOrder.cf.SS_SB
      Fori ←0, coalitions.length
            Ifcoalitions[i].getEnergySurplus() >=
        (buyOrder.energyDeficit +
        buyOrder.energyFlexibility)
            reward ← coalitions[i].
        getTokenRewardForBuyer(
         buyOrder.energyDeficit,
         buyOrder.energyFlexibility, buyOrder.state)
            If reward > _cf / 10 ∗
        buyOrder.energyFlexibility
              If reward > maxRreward
              maxReward ← reward
               selectedCoalition ←i
              End If
            End If
          End If
      End For
      coalition[selectedCoalition].requestAddBid
        (buyOrder)
      buyOrders[buyOrder.buyerEfe] ← buyOrder
      Emit RegisterBuyOrder(buyOrder, block.timestamp,
        address( coalition[selectedCoalition]))
      Return address( coalition[selectedCoalition])
End
```

Algorithm 5 Smart Contract CooperativeTradingSession for creation of the prosumers' grand coalition

```
1:  Function createGrandCoalition
2:      Input: msg.sender, certificateAddress
3:      Output: -
4:      Begin:
5:        sellOffer←new SellOfferCooperative()
6:        sellOffer.seller ←address(this)
7:        For i ←0, partiallyStableCoalitions.length
8:            sellOffer.energySurplus + =
          partiallyStableCoalition.getEnergySurplus()
9:            sellOffer.payoff.buyer + =
          partiallyStableCoalition.getPayoffBuyer()
10:           sellOffer.payoff.selfSufficient + =
          partiallyStableCoalition.getPayoffSelfSufficient()
11:       End For
12:       sellOffer.payoff.buyer/ZZZZZ/=
          partiallyStableCoalitions.length
13:       sellOffer.payoff.selfSufficient /=
          partiallyStableCoalitions.length
14:       grandCoalition ←new Coalition(sellOffer)
15:       For i ←0, partiallyStableCoalitions.length
16:           amount ←
          partiallyStableCoalitions[i].getEnergySurplus() ∗
          sellOffer.payoff.selfSufficient / 100
17:           partiallyStableCoalitions[i].
          transferTokensToGrandCoalition
          (address(grandCoalition), amount)
18:       End For
19:       energySurplus ← grandCoalition.getEnergySurplus()
20:       For i ←0, unassignedBids.length
21:           unassignedBids[i].cf /= 2
22:           buyOrder ← unassignedBids[i]
23:           _cf ← buyOrder.state == BUYER ?
          buyOrder.cf.SB_SS:buyOrder.cf.SS_SB
24:           reward ←
          grandCoalition.getTokenRewardForBuyer(
          buyOrder.energyDeficit,
          buyOrder.energyFlexibility, buyOrder.state)
25:           If reward > _cf / 10 ∗
          buyOrder.energyFlexibility
26:           grandCoalition.requestToAddBidSecondStage
          (buyOrder)
27:           End If
28:       End For
29:        grandCoalition.acceptBidsSecondStage()
30:       If grandCoalition.isStable
31:         grandCoalition.transferTokensToMembers()
32:       End If
33: End
```

the coalition (line 29). Buyers are evaluated first, and the ones with a higher energy deficit are more likely to be selected. The self-sufficient prosumers are evaluated only if the energy surplus of the coalition is not completed after accepting the buyers. If the grand coalition is in a stable phase the tokens are sent to its accepted members (lines 30 – 32).

IV. EVALUATION RESULTS

In the evaluation, we have considered 30 small-scale prosumers leveraging the monitoring infrastructure and profiles described in [11]. They are split into disjoint subsets as follows: 8 prosumers have a surplus of renewable production and will act as sellers; 17 prosumers have higher energy consumption and will act as buyers and 5 prosumers are in a balanced state having the demand approximately equal with the consumption.

Table 2 shows the characteristics of the prosumers used in the evaluation. The energy features are estimated for a window of 6 hours. In the case of sellers (IDs 1-8), the energy surplus is represented in kWh, whilst the uncertainty and the payoffs are percentages. The payoff distribution will depend on the type of prosumers that will bid for using the energy surplus and used to determine the tokens' distribution. The uncertainty is computed considering the historical transactional data of the prosumer and is related to the stochastic nature of the renewable generation which is dependent on weather. The energy buyers have a deficit in energy due to the higher energy demand than generation thus they will seek to join in coalitions to cover it. The self-sufficient prosumers have neither an energy deficit nor a surplus but have significant flexibility levels to contribute to coalitions. Flexibility indicates percentual by how much they can reduce or increase their energy consumption. Their change in flexibility has an associated cost, depending on the current prosumer state: smaller for the buyers but higher for the self-sufficient ones.

TABLE 2. Characteristics of prosumer used in evaluation.

Prosumers - Energy Sellers				
Prosumer IDs	Energy Surplus (kWh)	Uncertainty (%)	Payoff (%)	
			Buyers	Self-Sufficient
[1 – 5]	[100-500]	[10-15]	[25-40]	48-70
6	1000	11	22	52
7	2200	11	18	50
8	3000	10	15	45
Prosumers - Energy Buyers				
Prosumer IDs	Energy Deficit (kWh)	Flexibility (%)	Shifting Cost Factor	
[9-22]	[30-550]	[5-60]	[1-3]	
23	1200	5	1	
24	1300	24	1	
25	2000	5	3	
Prosumers - Energy Self-Sufficient				
Prosumer IDs	Energy Consumption (kWh)	Flexibility (%)	Shifting Cost Factor	
[26-30]	[50-1000]	[20-70]	[6-8]	

```
1.  {
2.    "name": "SelfSufficientCommunity",
3.    "engine": {
4.      "authorityRound": {
5.        "params": {
6.          "stepDuration": "5",
7.          "validators": {
8.            "list":
    ["0x04fb94f5e2555d1e860462060337aa62ec6e919d"]
9.          }   }   }   },
10.   "params": {
11.     "gasLimitBoundDivisor": "0x400",
12.     "maximumExtraDataSize": "0x20",
13.     "minGasLimit": "0xffffffff",
14.     "networkID": "0x2323",
15.     "eip155Transition": 0,
16.     "validateChainIdTransition": 0,
17.     ...
18.   },
19.   "genesis": {
20.     "seal": {
21.       "authorityRound": {
22.         "step": "0x0",
23.         "signature":  "0x0000…"
24.       }
25.     },
26.     "difficulty": "0x20000",
27.     "gasLimit": "0xffffffff"
28.   }
29.   …
30. }
```

FIGURE 3. chainspec.json file for Ethereum private chain configuration.

We have implemented our model on a private Ethereum network which was customized using the chain specification file presented in Figure 3. We opted for a Proof-of-Authority consensus algorithm with a time slot of 5 seconds between blocks (lines 4-9). The chain specification file enables configuration of chain parameters such as gas limits, maximum size (lines 10-18) as well as the genesis block (lines 19-28). For each prosumer in the community accounts have been created. The gas price can be established depending on the community rules and can be configured by specifying it as a transaction parameter.

We use the proposed governance model using cooperative games to support the creation of prosumers coalitions in self-sufficient energy communities. The seller prosumers will use their smart contracts to initiate coalitions by placing sell offers and manage the incoming bids for joining the initiated coalition aiming to reach a stable state. The sellers generate the payoff rewards using LERC20 tokens and digitize the delivered energy using ERC721 tokens to keep an immutable link with the generation source (i.e., prosumer ID).

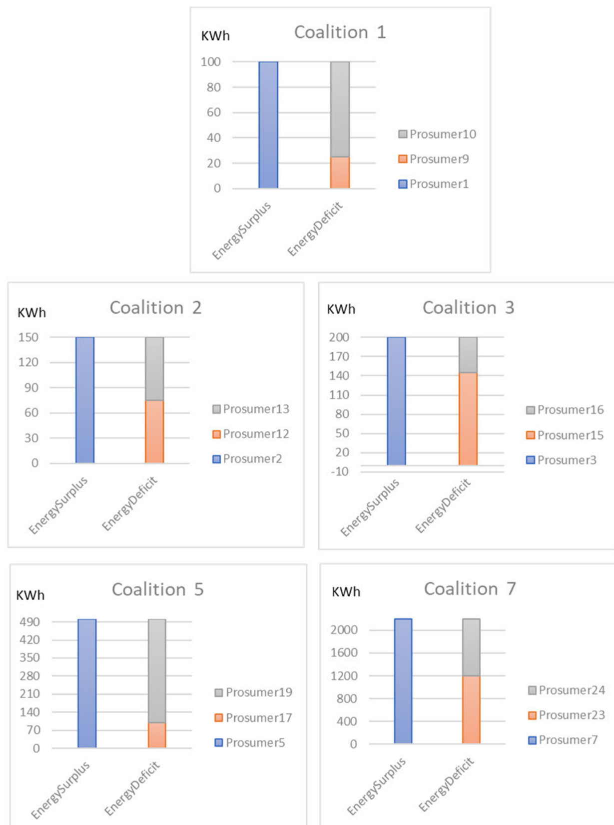

FIGURE 4. 1st stage stable coalitions.

Figure 4 shows the stable coalitions generated in the first stage of the cooperative game. The coalitions created are self-sufficient balancing the energy supply and total aggregated energy demand. The coalition is initiated by sellers by transferring the quantity of LERC20 tokens to the smart contract to be utilized to reward the buyers or self-sufficient prosumers for joining the coalition based on their contribution. The quantity of tokens is determined considering the payoff percentage for self-sufficient prosumers from the energy surplus amount of the seller prosumer. This way, the coalition will have enough tokens to spend even in the case it reaches a stable state only with self-sufficient prosumers that have higher rewards than buyers. ERC721 energy tokens are minted by the prosumers when the coalition is created with the energy surplus quantity and gives the coalition allowance to transfer tokens.

TABLE 3. Stable coalition and tokens distribution.

Coal. ID	LERC 20 Tokens	ERC721 Tokens ID: quantity	Pros. ID	Flexibility Used	LERC20 Reward	Received ERC721 Tokens
1	70	0: 100	9	5	14	25
			10	0	30	75
			26	0	0	0
			27	0	0	0
			29	0	0	0
2	97	1:150	12	15	36	75
			13	0	26	75
3	120	2:200	15	0	46	140
			16	20	33	60
5	240	4:500	17	30	44	100
			19	0	112	400
7	1100	6:2200	23	0	216	1200
			24	300	288	1000

Table 3 presents the quantity of LERC20 and ERC721 tokens received by the prosumers as rewards for their participation for the stable coalitions. The prosumers check if the initiated coalitions can satisfy their energy deficit and choose the coalition with the highest reward. For example, Prosumer with ID 9 chose the coalition with ID 1 initiated by Prosumer with ID 1.

Even though it has an energy deficit of 75 kWh and only 70 kWh are needed to make the coalition stable after the acceptance of Prosumer with ID 10 having an energy deficiency of 30 kWh. Thus, 5 kWh of the prosumer with ID 2 were mitigated by decreasing its consumption by shifting flexibility and will receive an additional reward for the flexibility usage.

The coalitions that are partially stable (i.e., ID 6) as well as coalitions initiated by sellers which have not received any request to join from buyers are presented in Figure 5. The coalitions are not self-sufficient, the energy demand and supply being unbalanced thus they are destroyed, and the prosumers members will enter the second stage of the cooperation.

At the same time, some prosumers were not accepted in any coalition in the first stage (see Table 4).

There are several reasons for this. The prosumer with IDs 11, 14, 18, 20, 22, and 25 requested to join the coalition with ID 1 but was not accepted as the sellers had selected

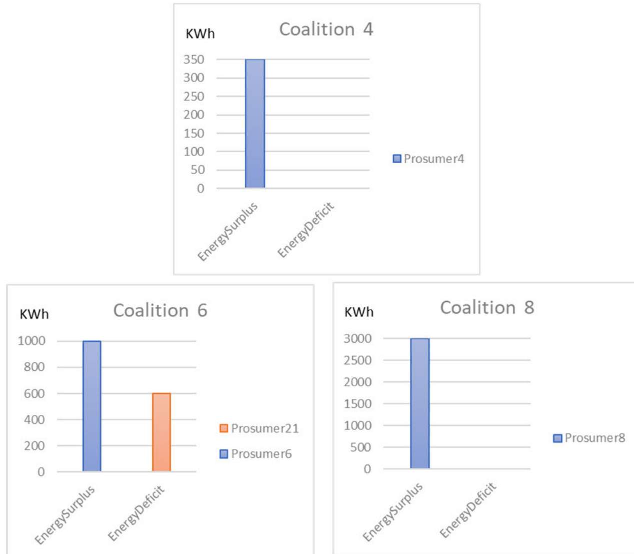

FIGURE 5. 1st stage unstable or partially stable coalitions.

TABLE 4. Prosumers for second stage.

Prosumer ID	Energy Deficit (kWh)	Energy Surplus (kWh)	1st Stage Coalition ID: State	Reason
11	80	0	1: STABLE	Bid Rejected
14	130	0	3: STABLE	Bid Rejected
4	0	350	-	Cost>reward
18	260	0	5: STABLE	Bid Rejected
20	450	0	5: STABLE	Bid Rejected
6	0	1000	6: PARTIALLY-STABLE	> energy deficit
21	600	0	6: PARTIALLY-STABLE	Coalition state
22	550	0	6: PARTIALLY-STABLE	Bid Rejected
25	2000	0	7: STABLE	Bid Rejected
8	0	3000	-	Cost>reward
28	0	0	-	No bid or offer
30	0	0	-	No bid or offer

other bids to distribute their surplus. Other prosumers were accepted in partially stable coalitions, being destroyed in the second stage (e.g., prosumers with IDs 21, 4, and 8). The partially stable coalitions that were not selected by any prosumer will be destroyed in the second stage and forming a coalition with their aggregated energy surplus. The prosumers that didn't select a coalition in the first stage because the reward was smaller than their cost associated with flexibility will also enter the second stage (i.e., prosumers with IDs 28 and 30).

TABLE 5. Grand coalition – second stage.

<table>
<tr><th colspan="2">Coal. ID</th><th>Energy Surplus (kWh)</th><th>Payoff Buyer</th><th>Payoff Self-Sufficient</th><th>Pros. ID</th><th>Flexibility Used</th><th>LERC20 Reward</th><th>Received ERC721</th></tr>
<tr><td colspan="2" rowspan="9">Grand Coalition</td><td rowspan="9">4350</td><td rowspan="9">21</td><td rowspan="9">52</td><td>11</td><td>0</td><td>16</td><td>80</td></tr>
<tr><td>14</td><td>0</td><td>27</td><td>130</td></tr>
<tr><td>18</td><td>0</td><td>54</td><td>260</td></tr>
<tr><td>20</td><td>0</td><td>94</td><td>450</td></tr>
<tr><td>21</td><td>0</td><td>126</td><td>600</td></tr>
<tr><td>22</td><td>0</td><td>115</td><td>550</td></tr>
<tr><td>25</td><td>0</td><td>420</td><td>2000</td></tr>
<tr><td>28</td><td>100</td><td>52</td><td>100</td></tr>
<tr><td>30</td><td>180</td><td>93</td><td>180</td></tr>
<tr><td rowspan="3">Prosumer IDs</td><td>4</td><td>350</td><td>25</td><td>50</td><td></td><td></td><td></td><td></td></tr>
<tr><td>6</td><td>1000</td><td>22</td><td>52</td><td></td><td></td><td></td><td></td></tr>
<tr><td>8</td><td>3000</td><td>18</td><td>55</td><td></td><td></td><td></td><td></td></tr>
</table>

In the second stage a grand coalition is created. All the energy surplus of prosumers unmatched in 1st stage are merged in a single sell offers (see Table 5). The reward tokens from the destroyed coalitions are transferred to the grand coalition, and the overall energy surplus is determined by adding up the surplus energy from the sell offers that initiated the coalitions. The payoffs for both buyers and self-sufficient prosumers are calculated as an average of the payoffs obtained from the first stage coalitions. The resulting energy surplus is 4350 kWh, with a payoff of 21% for buyers and 52% for self-sufficient prosumers.

Any bids for energy buy that were not accepted by a stable coalition in the 1st stage will be forwarded to the grand coalition. The buy orders are then sorted in a descending order based on their energy deficit, while the self-sufficient orders are kept in a separate array. All the buyers are accepted in the grand coalition, but additional flexibility from self-sufficient prosumers is required to achieve the needed energy deficit (100 kWh flexibility of prosumer with ID 28 and 180 kWh from flexibility of prosumer with ID 30).

Finally, the energy and reward tokens are distributed to the members of the grand coalition. The sum of all prosumers sell offers that enter the second stage represents the energy deficit of the grand coalition. As is shown in Figure 6, the energy surplus of the grand coalition is balanced with the remaining energy deficit.

Figure 7 shows the prosumers that are in a buyer or self-sufficient state and participated in coalition using their energy deficit and flexibility. The initial deficit represents the energy deficit of prosumers before using their flexibility, whilst the actual deficit represents the energy deficit of the prosumers after they were accepted in coalition and asked to use their flexibility if was needed for the stability of the coalitions.

Each prosumer receives payoff based on their individual contributions and usage of energy flexibility. The payoff distribution for prosumers is shown in Figure 8. The payoffs for the buyers are proportional to their deficit and energy flexibility used. Similarly, the self-sufficient prosumers receive payoffs proportional to the quantity of flexibility used. The tokens that remain in coalitions are allocated to the sellers.

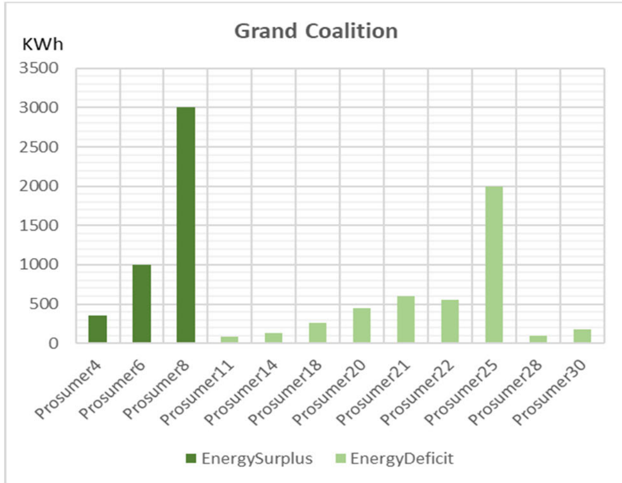

FIGURE 6. Coalition created in second stage.

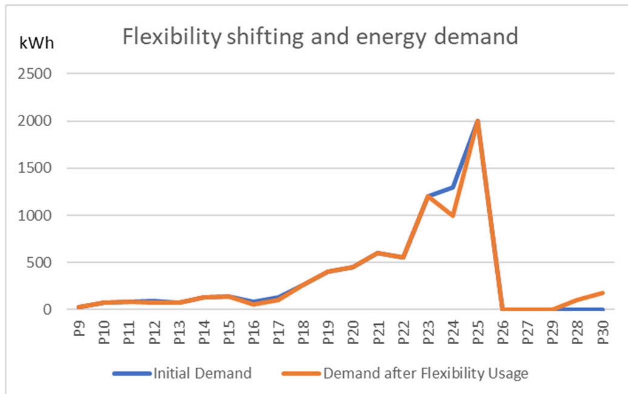

FIGURE 7. Flexibility of prosumers used in coalition.

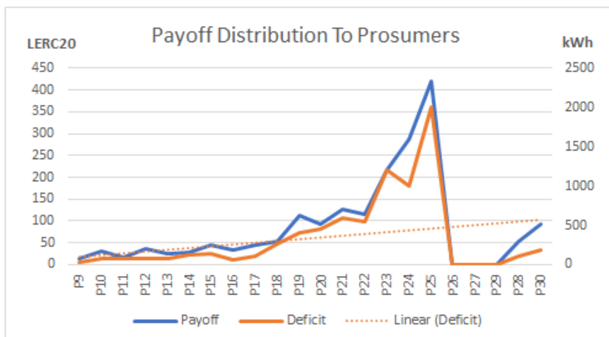

FIGURE 8. Payoff distribution in coalitions.

V. DISCUSSION

In this section, we conducted a public chain feasibility analysis of our model discussing the scalability issue in terms of blockchain gas consumption and transactional time as well as on model convergence. A private network configuration with gas features like those of the public chain was utilized to calculate the cost of running the model on the public chain.

Gas consumption is calculated based on the execution of computational operations and storage requirements within smart contracts and energy transactions as defined and operated by our model for self-sufficient energy communities. The unit of gas consumption is called "gas." Each smart contract operation has an associated gas cost determined by multiplying the gas consumed with the price in Ether. The transactional time refers to the duration for processing and storing the transactions generated by our model for self-sufficient energy communities on the blockchain network.

Table 6 presents the average gas consumption and processing time for blockchain transactions along with the operations involved in each transaction.

TABLE 6. Gas consumption for the operations defined.

Stage	Transaction	Smart Contracts Operations	Gas Cons.	Time (ms)
I	registerSellOffer	Place Sell Orders	4942816	4978
		Create Coalition		
		Mint Tokens		
	registerBuyOrder	Place Buy Orders	525433	4986
		Chose Coalition		
	acceptBids	Evaluate all received orders	770887	5081
		Compute token distribution		
		Transfer tokens		
II	create Grand Coalit on	Group remaining sell offers and create grand coalition	8900203	4582
		Transfer tokens to grand coalition		
		Send remaining buy orders to grand coalition		
		Evaluate and accept received orders		
		Transfer tokens to members		

The gas consumption for the register-buy-order transaction varies with the total number of created coalitions, as all coalitions are checked when a buy order is processed. Similarly, the gas consumption for the accept-bids transaction depends on the number of pending bids from each coalition. The gas consumption for the create-grand-coalition transaction depends on the number of buy orders and coalitions that will enter the second stage. The gas consumption and processing time of the register-sell-order transaction are similar with few variations across sellers (Figure 9).

The gas consumption for the place buy order transaction depends on the number of coalitions checked and the number of bids that are already pending in the coalition. During the place buy order transaction, the number of coalitions checked is given by the number of coalitions that can satisfy the energy deficit and flexibility from the bid order and have a reward higher than the cost associated with the flexibility. The buy order will be sent to a coalition that satisfies these constraints and has the highest reward. In the pending bids array the orders are kept descending by their cost associated with flexibility, thus if there are bid orders in the pending array, an additional computational effort is needed to keep the array ordered leading to higher gas consumption.

FIGURE 9. Gas and Time for register-sell-offer transaction.

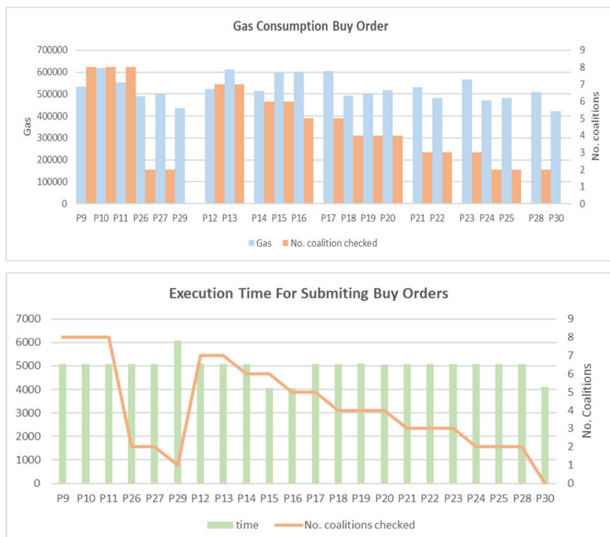

FIGURE 10. Gas and time overhead for register-buy-order transaction.

In Figure 10 – top the prosumers are grouped by the coalition they chose during the first stage, and they are represented in the same order in which the bids were placed. The gas consumption (primary axis) and the number of coalitions checked (secondary axis) can be seen for each prosumer. For example, Prosumer27 chose the first coalition after checking two coalitions that satisfy their needs, but the gas consumption is increased due to the operations involved to keep the bids ordered. As can be seen in Figure 10 - bottom the execution time for the place bid order transaction is independent of the number of coalitions checked.

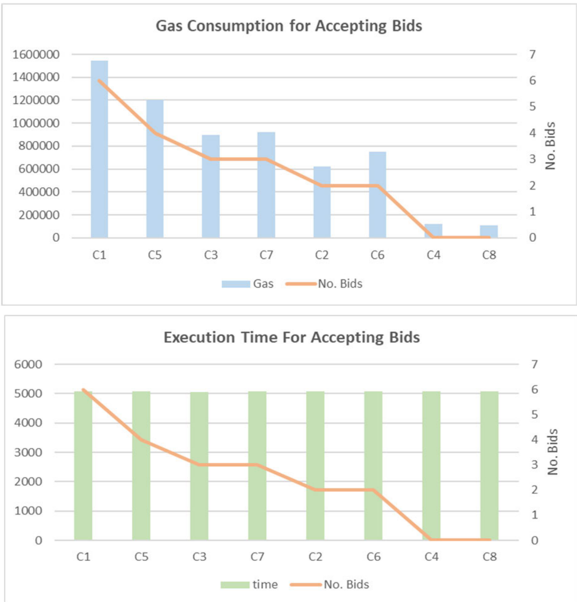

FIGURE 11. **Gas and Time for Accept Bids Transaction.**

The gas consumption for accepting bids in coalition (see Figure 11) is proportional with the number of bids from the pending bids array, whilst the transaction execution time is similar for different coalitions. During the accept bids transaction, each coalition evaluates the bids from the pending bids array and tries to accept the bids to achieve a stable state. Thus, the computational effort increases with the number of bids leading to higher gas consumption.

Table 7 shows the cost of the transaction's gas consumption in Ether considering a gas cost unit of $3*10^{11}$ Wei which is equivalent to 0.0000003 Ether. The higher gas consumption and costs make it unfeasible for public chains. Thus, private chains suit better not only from a cost perspective but also, align better with the objectives and goals of self-sufficient energy communities.

TABLE 7. **Gas consumption and cost for A public chain configuration.**

	Register		Accept Bids	Create Grand Coalition
	Sell Offer	Buy Order		
Gas	4942816	525433	770887	8900203
Cost (Ether)	1.4828448	0.1576299	0.2312661	2.6700609

Finally, we have analyzed the convergence of our proposed solution. In the defined model the stability shows that no prosumer or coalition has an incentive to diverge from the current solution that is achieving the balancing of energy demand and supply in the community, while ensuring a fair allocation of payoff among players. We have evaluated the convergence of our model, by conducting both imputation and core analysis to examine the conditions for stability.

Imputation analysis determines a payoff allocation scheme that provides to each prosumer a share of rewards that is at least as favorable as what they could obtain individually, and that no coalition can improve its members' payoffs by forming new coalitions. Additionally, it guarantees that the total payoff allocated to the prosumers does not exceed the value of the grand coalition. In our approach, we employ the Harsanyi dividend formula for payoff allocation, which ensures the distribution of payoffs is fair, and no prosumer can gain more by joining another coalition.

The core analysis determined the presence of a non-empty core indicating the existence of at least one stable solution for our self-sufficient energy community model. To converge two conditions must be met simultaneously. Firstly, the difference between generated energy and energy demand within each coalition should be close to zero. Our algorithm successfully forms coalitions of prosumers that balance energy generation and demand (see Figure 2 and 3). Secondly, our self-sufficient community model should ensure that no subgroup of players will desire to form a separate coalition and redistribute the payoff in a way that improves their outcomes without negatively impacting another player's outcome. To check this, we focused on determining whether any subgroup of prosumers could improve their position while adversely affecting the payoffs of other prosumers. We did not find any redistributive possibilities within the coalition structures showing that the current coalition structures and payoff allocations are robust.

VI. CONCLUSION

In this paper, we address the problem of prosumers integration and decentralized cooperation in energy communities by proposing a solution that joins blockchain and smart contracts with cooperative games. We define a model for energy communities of small-scale prosumers that may coordinate their demand, generation, and flexibility toward self-sustainability. For prosumers self-sufficient coalitions we have used cooperative games implemented on top of peer-to-peer energy trading and blockchain aiming to balance the local energy generation and demand. The model is implemented using self-enforcing smart contracts for optimized payoff distribution using tokens capturing the beyond-financial value interactions. The results obtained in a community scenario using prosumers metering energy profiles show the effectiveness of our solution in enabling prosumers to create energy-balanced coalitions. The model achieves a minimal difference between the energy consumption and production in the community of approximately 0.01%, implying a high level of self-sufficiency. The processing and execution time for the transactions on blockchain was low, being around 5 seconds indicating efficient processing. The feasibility analysis for running the proposed model on the public blockchain relieved higher gas consumption and costs making it suitable for private chains. However, private chains are better not only from a cost perspective but also, they align better with the objectives and goals of self-sufficient energy communities.

Making our model operational in energy communities that aim to achieve self-sufficiency is an ongoing activity of the European Bright Project [41] by considering several configurations of energy communities: renewable energy communities, local energy cooperatives, and virtual energy communities. Beyond the technical framework for implementing the model, several challenges need to be addressed, such as behavioral barriers, gaining social acceptance from community members and conforming to existing regulatory frameworks, and ensuring enough flexibility and market-level liquidity. Finally, our model has some limitations. The P2P energy trading in small energy communities can be affected by the lack of cooperation and coordination among participants due to their diverging objectives and preferences. Moreover, the lack of community participation and technology adoption may limit the model's effectiveness. Additionally, the prosumers may have limited awareness of other's flexibility capabilities, and the prediction of energy generation or consumption patterns in the day ahead can be seriously affected by the quality of the prediction model resulting in higher levels of uncertainty. Furthermore, the lack of trust among participants can be a serious limitation same as the possibility that prosumers may not adhere to the agreed-upon cooperation agreements or trading rules, disrupting the cooperative balance and stability of the proposed solution.

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