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Blockchain-Based Decentralized Virtual Power Plants of Small Prosumers

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ABSTRACT The deployment of small-scale renewable energy sources will transform the management of energy grids towards more decentralized solutions in which the prosumers will have a more active role. Regulatory and market barriers are driving the implementation of virtual aggregation models in which the small-scale prosumers work together on a larger scale to gain benefits that could not be obtained on an individual basis. In this paper, we propose to use public blockchain and self-enforcing smart contracts to construct Virtual Power Plants (VPPs) of prosumers to provide energy services. A model has been defined for capturing the prosumer level constraints in terms of available energy profiles and energy service requirements enabling their optimal aggregation in hierarchical structures. A lightweight decentralized solution for VPPs construction is implemented using smart contracts enabling its efficient running on the public blockchain. Smart contracts are encoding the model constraints and are defining functionalities for prosumers to initiate or join a VPP implementing the complete chain of Offer-Operate-Measure-Remunerate actions. The VPP will be managed on top of a distributed ledger technology offering decentralized functionality for tracking and validating the delivery of energy based on the blockchain transactions and for energy and financial settlement, the remuneration being done according to the amount of energy provided by individual prosumers. Experimental results show that the proposed solution runs successfully on the public blockchain with good execution time and can address Balancing Responsible Party requests for additional generation. The overhead in terms of gas consumption and transactional throughput stays within reasonable boundaries.

INDEX TERMS Public blockchain, virtual power plant, smart contract, small prosumers, distributed ledger technology, peer to peer energy trading.

I. INTRODUCTION

The deployment of small-scale renewable energy resources had enabled the adoption of new business models in which the producers and consumers (prosumers) are enabled to participate in the management of the energy system. Nowadays regulatory and economic factors are driving the implementation of virtual aggregation models in which the small-scale prosumers work together on a larger scale to gain benefits that could not be achieved on an individual basis [1]. For example, even though Demand Response (DR) is acknowledged as a significant service for reducing the grid management costs, the potential reward from participation makes such programs unattractive for small individual prosumers. Moreover, the minimum thresholds for participation in energy markets are too large for allowing the participation of single-family houses that have renewable energy generation capacity. According to [2], to operate on the national markets, several constraints need to be met, making the prosumers ineligible for trading on these markets: a minimum bid or offer size, symmetric bidding requirements (e.g. both upwards and downwards flexibility), activation time (e.g. reserves can be required to be online up to 10 hours). For these reasons, the actors of the energy markets are usually retailers, large power plants, etc.

Finally, the high energy prices, the improvement of renewable technology, and lowering deployment costs are also drivers for the implementation of virtual models. They may

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combine the need for decarbonization and local community sustainability goals with the delivery of energy services to the main grid [2], [3]. The virtual aggregation models may successfully mitigate and address grid-level value streams and operational constraints with local management of prosumers and communities [4], [5]. The small-scale prosumers can provide a good opportunity for decarbonizing the energy system, while at the same time reducing pressure on the local grid and contributing to their economic development. In this way, the local community of residents will be engaged in the optimized cooperative management of non-grid owned (e.g. consumers-owned) distributed renewable energy sources, and/or in participating in shared investments in district-level renewable generation and storage.

In the computer science field, lately, there is a growing interest the blockchain technology and its usage for decentralizing the energy system [6], [7]. Blockchain-based systems have been implemented in different sectors of the economy. They provide effective ways to: reduce costs, improve control, and competition among small size suppliers and the large traditional ones. Blockchain-based systems are mostly used for those domains that are characterized by high demand variability, diversity, and low granularities or scales. These are also characteristics of nowadays power networks that must deal with the rise and deployment of small-scale prosumers. There are several advantages of using the blockchain for smart energy grid management. Most of them are linked to the technical characteristics and working principles of blockchain. First is the decentralization of trust allowing the prosumers to trade energy among them in a peer to peer fashion. Second is the immutability of blockchain which ensures that all energy transactions once registered in the distributed ledger will not be modified. The third is the token-based digitization of energy allowing it to be traded as an asset and to be tracked until the moment of creation in the blockchain. Forth is the distributed database of energy transactions enabled by the blocks replication and consensus mechanism empowering each peer node to validate the state of the ledger. Finally, is the use of self-enforcing smart contracts that can encode business rules at the peer node level which can automatize de delivery of energy services as also as a means of enforcing a decentralized control of energy assets. So, the blockchain stores the tamper-proof log of energy transactions while the smart contracts the rules that need to be verified and enforced by peer nodes [8], [9]. They are triggered by transactions calls that require a distributed ledger state update considering the smart contracts execution results.

In this context, the decentralized management of prosumers energy loads and supply is an emerging trend that facilitates the implementation of collective actions for assuring the self-supply of local energy demand. The local energy communities may become a stakeholder able to identify and manage the members' energy needs and contribute to the smart grid resilience. Along such innovation trajectory, Virtual Power Plants (VPPs) can be constructed by prosumers to aggregate the locally generated renewable energy and trade it on the wholesale market to other stakeholders such as the Balancing Responsible Parties (BRPs) (see Figure 1).

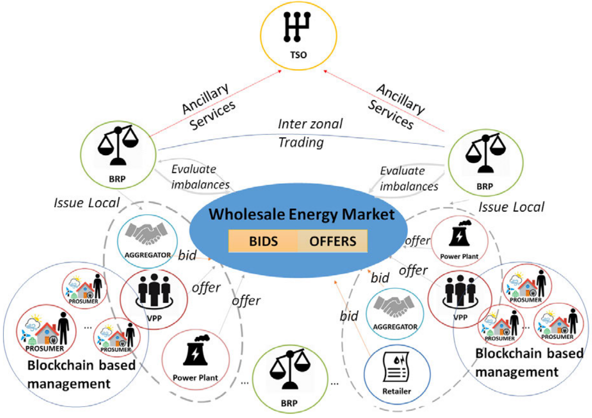

FIGURE 1. VPP of small-scale prosumers and energy delivery.

The BRPs are assigned to wider regions of the grid. They evaluate possible imbalances between production and consumption [10], [11] and take corrective measures to achieve a balanced position. For balancing actions with a granularity higher than 15 minutes, the BRP registers orders during the intra-day trading period to access cross zonal resources such as the flexibility and energy generation provided by the VPPs.

To provide the required energy service one should select, aggregate, and coordinate local energy production sources and flexible assets featuring controllable loads. In our vision, blockchain technology with its advantages will improve the phases of this process. All prosumers in a local community will be registered as peer nodes of the blockchain network, and the monitored energy data is stored as energy transactions in the distributed ledger. Using block replication all the other peers be made aware of the exact levels of local energy consumption and production. The self-enforcing smart contracts define the prosumer level constraints concerning the energy demand, generation, and available flexibility. The constraints are automatically enforced based on monitored energy data and are used to construct prosumers' bids for joining the VPP. In this way, the selection of the VPP members is automated. After a prosumer joins a newly created VPP, the service level constraints can be automatically injected into its smart contract for monitoring the actual energy delivery. These contracts are also registered in the blockchain, similarly with the transactions. Thus, all prosumers will validate the integrity of the executed actions such as energy tokens issued, bids and offers, monitored energy values, etc. In this way, the energy and financial settlement of the VPP can be carried out in a decentralized manner without needing the validation of a trusted third-party intermediary.

In this way, active and reactive power of energy resources connected in the distribution network might be aggregated and coordinated in VPPs to provide energy or ancillary services to either Transmission System Operator or Distribution System Operator (DSO). VPP can, therefore, perform ancillary services such as aggregated active power to ensure tertiary reserve for the Transmission System Operator (TSO) by using a hierarchy of aggregations. Also, it may aggregate reactive power for performing voltage secondary control for the DSO and exchange of a controlled reactive power with the TSO, thus providing for its specific ancillary services. However, if the granularity is smaller than 15 minutes, it is the responsibility of the TSO to balance the grid by reducing or increasing the demand and supply. This is possible by accessing reserve assets that are directly contracted.

In this paper, we propose a hierarchical solution for constructing and managing VPPs composed of small-scale prosumers using blockchain and self-enforcing smart contracts. We bring the following novel contributions:

- A model for prosumers optimal aggregation in VPPs to meet energy service requirements and minimize the energy cost while considering prosumers constraints such as available flexibility, production, storage, etc.
- A lightweight decentralized solution for VPPs construction using hierarchical structures and smart contracts enabling its efficient running completely on a public blockchain. It allows to couple prosumer smart energy meter with a self-enforcing smart contract that will also define as rules the prosumer energy constraints and preferences such as time of delivery and energy price. The smart contracts feature functionalities for prosumers to initiate the construction of a hierarchical VPP by opening an energy trading session or to join a VPP by placing energy offers according to its constraints and preferences.
- A solution for energy delivery tracking and financial settlement of VPP hierarchical structure on top of the blockchain implementing the complete chain of Offer-Operate-Measure-Remunerate actions. Energy market or service level objectives are injected as business rules into the prosumers' smart contracts to set the amount of energy to be delivered. This will provide the decentralized functionalities for VPP operation such as aggregate and offer before gate closure by using energy transactions stored in a blockchain and finally the near real-time validation, settlement, and remuneration according to the amount of energy provided by individual prosumers.

Table 1 describes the terms and technical abbreviations used throughout the paper.

The rest of this paper is organized as follows: Section II presents the existing state of the art literature in the area of decentralized management of VPPs, Section III details the proposed VPP model, Section IV presents the blockchain-based solution for organizing and managing prosumers in VPPs, Section V presents relevant experiments and results and finally, Section VI concludes the paper.

II. RELATED WORK

The decentralized aggregation of prosumers in VPPs to provide energy services is only tangential addressed by the

TABLE 1. Abbreviations and letter symbols.

Abbreviation	Unit or Term
Π_{EES}	Maximum capacity of the storage system
Φ_{MAX}	Maximum charging rate
Ψ_{MAX}	Maximum discharging rate
B^k	Total baseline energy consumption of prosumer k
C^k	Energy consumption of the prosumer k
E_{MAX}^k	Maximum energy amount prosumer k may provide
E_b	Baseline energy profile
E_{bid}	Amount of energy demand
E_c	Energy demand profiles
E_f	Flexibility loads
E_g	The energy generation profiles
E_{offer}^k	Amount of energy over the service delivery interval
E_s	Actual storage capacity
F^k	Energy flexibility that may be shifted
P_{MAX}	The upper limit on the power that may be generated
P_{offer}^k	Prosumer energy offer associated a price
VPP_{bid}	Bid request to join a VPP
VPP_{offer}	Smaller VPP energy offers to join a VPP
$prosumer^k$	Prosumer k
σ_{EES}	Actual discharging rate
φ_{EES}	Actual charging rate
BRP	Balancing Responsible Party
DLT	Distributed Ledger Technology
DR	Demand Response
EES	Electrical Energy Storage
IoT	Internet of Things
kWh	Kilowatt-hour
P2P	Peer to Peer
PV	Photovoltaics
RES	Renewable Energy Sources
TSO	Transmission System Operator
Tx	Transaction
VPPs	Virtual Power Plants
Wei	Digital currency for Ethereum transactions.
DoD	Maximum depth of discharge
G	Total energy generation
S	The total energy of the prosumer energy storage system that may be used during service delivery
T	Optimization time horizon (T_S – start and T_E – end)
mem	VPP member
α	A layer of the VPP hierarchy
τ	Binary array states reflecting if a prosumer or a smaller VPP is a member or not in the current VPP
x_i	Binary Decision

state-of-the-art literature even though technological enablers such as blockchain and Peer to Peer (P2P) energy trading show great potential.

Most works in the field are dealing with the development of multi-criteria optimization heuristics for scheduling various energy assets participation in the VPP to meet service level objectives [12]–[14]. Modeling solutions for optimal scheduling are either deterministic or stochastic. The optimization problem is most of the time modeled as mixed-integer linear programming and used to assist VPP managers in making medium-term energy trading and increasing the profit [15], [16]. The stochastic solution considers factors such as the uncertainties about the prediction of market price, energy demand, or generation in the VPP's optimal operation. VPP architectures and optimization solutions are proposed for aggregating building-side energy resources to participate in the wholesale power market and distribution network-side regulation market [17]–[19]. Some authors are aiming to minimize the community costs by reducing the positive values representing the buying of energy from the community (consumption) with the negative values representing the selling of energy to the community (production) [20], [21]. Models for considering other energy vectors such as thermal energy are investigated aiming to gain even more VPP level flexibility targeting the participation in spinning reserve markets [22], [23]. The main problem with these solutions is that they are in general expensive when it comes to computational aspects such as time and resources, being difficult to be integrated with decentralized technologies such as blockchain.

Few approaches are addressing the decentralized construction and management of VPP even though it has the potential of removing some of the barriers [24]–[26] for prosumers engagement such as the need for local governance, insufficient consideration of their needs and local constraints, data centralization and privacy concerns. Blockchain and smart contracts assure a high level of decentralization and may successfully address local constraints and community needs [27]. The authors of [28] propose a Federated Power Plant, leveraging on the potential of P2P markets to find opportunities for the registered prosumers to form coalitions and participate in the wholesale energy markets. This is considered as a potential alternative model to the centralized VPP coordination strategies problems in which the coordinator may not have all the time the interest to find the optimal solution for the prosumers needs. A community-driven platform for flexibility provision that uses a Distributed Ledger Technology (DLT) is proposed in [29]. The communities form VPPs mainly with individual prosumers with Photovoltaic (PV) infrastructure targeting to provide ancillary services to the electrical power system. For coordination, the authors propose a heuristic algorithm combined with the blockchain via Oracles and democratic consensus of the community. In [30] the authors describe blockchain-based transaction management inside a VPP. The energy nodes can register their predicted trade amount, price, and hour, while the VPP aggregator is responsible for the transaction management. A continuous double auction mechanism is employed over the registered purchase and sales to ensure P2P energy transactions within the VPP. A similar solution is detailed in [31], where a P2P energy trading mechanism is implemented for settling energy transactions inside a VPP. However, the authors propose the use of an English auction system for each agent that wants to enter the energy market and trade energy. In [32] the authors propose a VPP decentralized energy trading solution that uses P2P mechanisms. A stochastic optimization model is defined to consider the uncertainties of wind and PV power sources while a multidimensional willingness bidding strategy is used for P2P negotiations. Smart contracts for energy trading in VPPs are described in [33], implementing a blockchain-based VPP transaction model. DLT is used to store the accounting data from the electricity trading such as the financial settlement data and electricity monitored data. A proof of concept for a self-organizing community of prosumers is presented in [34]. A decentralized control solution is implemented using smart contracts and validated with success on four households for two days' activity. The authors of [35] present a decentralized cooperative framework for addressing DR programs. Their purpose is to manage the daily energy transactions between a group of buildings having renewable energy sources on-premises. The proposed mechanism consists of a day-ahead community-level planning phase and an online tracking and monitoring phase, smart contracts being used to compute the aggregated cost function based on each participant's input. Authors of [36] propose a blockchain-based mechanism for grouping prosumers for better profits in the P2P market operations. A greedy algorithm is applied to take into consideration factors like the prosumer's locality, the reliability factor depending on the type of energy provided, and the actual amount provided. Finally, in [37] a decentralized energy consumption game is proposed to minimize the costs of the entire community by optimizing the consumption of the individual consumers. The purpose is to determine a plan for scheduling the appliances such that to minimize the operational cost using a branch and bound solution implemented using smart contracts.

Analyzing the reviewed literature, the following several gaps are identified. Most of the existing studies are focused on the business process of VPP peer to peer energy trading and not on the usage of blockchain for the actual VPP construction. They require well-known energy levels for their members to guarantee energy distribution. Small scales prosumers are rarely considered with insufficient consideration of their needs and local constraints. Existing blockchain-based solutions are using heuristics for aggregating the prosumers in VPP to meet a market service and such algorithms cannot be executed on blockchain due to its costs. Some authors even consider that the public blockchain-based solutions cannot be truly decentralized because of the Oracle usage for heuristics and they use private deployments that have some prosumers participation. Finally, they lack a mechanism for injecting energy service goals as rules into the smart contracts associated with prosumers enabling the truly decentralized tracking and settlement of delivery.

In this paper, we address the identified gaps by proposing a public blockchain-based solution for VPPs construction that provides a trackable, auditable, and decentralized aggregation of small prosumers. A model has been defined for optimal aggregation of energy prosumers using a hierarchical structure to meet the energy service requirements and minimize energy cost while considering prosumers' constraints in terms of available generation, storage flexibility, etc. Model decentralization and integration with the blockchain is achieved by using smart contracts that capture model constraints and defined operations while enforcing each prosumer's responsibility in tracking and validating the promised energy value delivery. Even though blockchain can guarantee decentralization, due to security reasons, each instruction executed on the blockchain has an additional overhead which sometimes can be substantial. A feasible implementation on the public blockchain needs to be lightweight in terms of consumed gas and transaction throughput. Our blockchain solution for VPP construction meets is exclusively implemented using smart contracts thus being lightweight and decentralized. The defined smart contracts allow the construction of hierarchical VPP structures in a truly decentralized manner running completely onto the public blockchain avoiding the Oracle problem mentioned in the literature.

III. VIRTUAL POWER PLANT MODEL

We consider a set of N energy prosumers from a local energy system or community that are willing to participate in a VPP to provide energy services to the main grid:

$$Prosumer[N] = \{prosumer^k | k \in \{1 \dots N\}\} \tag{1}$$

The prosumers considered are small scale in terms of energy profiles like regular households featuring renewable energy generation units, electrical energy storage units, and flexible energy demand. We define $T = [T_S, T_E]$ as the optimization time horizon for service delivery, E_g the energy generation profiles, E_c the energy demand profiles, and E_s the energy storage profiles:

$$prosumer^k = < E_g^k(t), E_c^k(t), E_s^k(t) >, \quad \forall t \in T \tag{2}$$

The energy generation profiles are determined by the energy production capability of the prosumer. They are related to the actual physical components involved in the generation, such as photovoltaic panels (PV panels) or wind turbines, and dependent on the local weather forecast. The total energy generation G of a prosumer is bounded during the energy service delivery interval T:

$$G^k = \sum\nolimits_{t=T_s}^{T_E} E_g^k(t) \tag{3}$$

$$0 \le G^k \le \int_{T_S}^{T_E} P_{MAX}(t)dt, \quad \forall k \in \{1 \dots N\} \tag{4}$$

where P_{MAX} is the upper limit on the power that may be generated.

The prosumer's energy demand profiles are adjustable being characterized by energy flexibility that can be shifted outside of the energy service delivery interval. The flexibility loads (E_f) are mostly driven by the adjustable energy demand of comfort or ambient assistive services such as illumination or air conditioning based on the residents' preferences. The energy flexibility that may be shifted is calculated as:

$$F^k = \sum\nolimits_{t=T_s}^{T_E} E_f^k(t) \tag{5}$$

In this way, the energy consumption of the prosumer can be reduced or increased with the baseline energy profile (E_b) that represents the regular energy profile in the absence of the service:

$$E_c^k(t) = E_b^k(t) \pm E_f^k(t), \quad \forall t \in T \tag{6}$$

The total baseline energy consumption is determined as:

$$B^k = \sum\nolimits_{t=T_s}^{T_E} E_b^k(t) \tag{7}$$

By decreasing their energy consumption below the baseline, the saved energy can be used to increase the amount of energy provided to the energy service. The energy consumption of the prosumer is determined as:

$$C^k = \sum\nolimits_{t=T_s}^{T_E} E_c^k(t) \tag{8}$$

and it is bounded as:

$$B^k - F^k \le C^k \le B^k + F^k \tag{9}$$

The prosumer's energy storage system profiles are determined by the charging or discharging of the on-site available batteries. Based on the battery characteristics we consider in our model: the maximum capacity of the Electrical Energy Storage (EES) system, Π_{EES}, the energy storage profile E_s, the maximum depth of discharge DoD, the actual charging φ_{EES} and discharging rates σ_{EES}, and finally, the maximum charging and discharging rates Φ_{MAX}, Ψ_{MAX}. The following constraints define the safe operation of the battery system:

$$\Pi_{EES} * DoD \le E_s^k(t) \le \Pi_{EES}, \quad \forall t \in T \tag{10}$$

$$0 \le \varphi_{EES}^k(t) \le \Phi_{MAX}^k, \quad \forall t \in T \tag{11}$$

$$0 \le \sigma_{ESS}^k(t) \le \Psi_{MAX}^k, \quad \forall t \in T \tag{12}$$

The total energy of the prosumer energy storage system S that may be used during energy service delivery is:

$$S^k = \int_{T_S}^{T_E} \sigma_{ESS}^k(t)dt - \int_{T_S}^{T_E} \varphi_{EES}^k(t)dt \tag{13}$$

The energy still available in a battery at the end of the delivery interval is determined as:

$$E_s^k(T_E) = E_s^k(T_S) + \int_{T_S}^{T_E} \varphi_{EES}^k(t)dt - \int_{T_S}^{T_E} \sigma_{ESS}^k(t)dt \tag{14}$$

The prosumer maximum amount of energy over the service delivery interval is computed as the energy quantity of energy that can be injected into the grid, considering the local generation, the stored energy, and flexibility:

$$E^k_{offer} = G^k + S^k - \left(C^k - F^k\right) \tag{15}$$

The prosumer energy offer will have associated a price, P^k_{offer}, and the energy amount will be always bounded above by the maximum amount of energy it may provide considering that its available energy is higher than its consumption:

$$0 < E^k_{offer} \leq E^k_{MAX} \tag{16}$$

$$C^k - F^k < G^k + S^k \tag{17}$$

The bid request to join a VPP is driven by the energy service request and features an amount of energy demand E_{bid}, the reward offered for prosumers to deliver the energy and the interval for delivery:

$$VPP_{bid} = \{E_{bid}, Reward, [T_S, T_E]\} \tag{18}$$

A VPP on layer α of the hierarchy will be created using a subset of prosumers from layer 0 and smaller VPPs from layers $\alpha - 1, \alpha - 2, \ldots, 1$. We define, τ, a binary array of length $N + M$, where N is the number of prosumers and M of the smaller VPPs. $\tau_i \in \{0, 1\}$, states if a prosumer or a smaller VPP is a member or not in the current VPP:

$$\begin{aligned} VPP^{\alpha} = \{&mem[i] | i \in \{1, N+M\}, \\ &mem \in Prosumer \cup \{VPP^{\alpha-1}\} \, and \tau_i = 1\} \end{aligned} \tag{19}$$

Also, VPPs from layers $\alpha - 1, \alpha - 2, \ldots, 1$ can submit energy offers to join a VPP on level α:

$$VPP_{offer} = \{E_{offer}, P_{offer}\} \tag{20}$$

The energy offer of a VPP is aggregating all the energy offers of its members until the bid energy demand is meet and the total energy prices are lower than the reward:

$$E_{offer}\,(VPP) = \sum\nolimits_{i=1}^{M+N} \tau_i * E^i_{offer} \tag{21}$$

$$\sum\nolimits_{i=1}^{N+M} \tau_i * P^i_{offer} \leq Reward \tag{22}$$

$$\sum\nolimits_{i=1}^{M+N} \tau_i * E^i_{offer} \geq E_{demand} \tag{23}$$

The VPP construction optimization problem is modeled as a constraint satisfaction problem featuring the constraints defined in relations above and an objective function that is aiming to minimize the distance between the energy demand of the bids and aggregated amount of the offers of the VPP members:

$$MIN\left(distance\left(E_{bid}, \sum\nolimits_{i=1}^{N+M} \tau_i * E^i_{offer}\right)\right) \tag{24}$$

The cost of the energy aggregated by the VPP is minimized by selecting and updating the member with the prosumers with the best price offers while meeting the energy constraints:

$$MIN\left(\sum\nolimits_{i=1}^{M+N} \tau_i * P^i_{offer}\right) \tag{25}$$

TABLE 2. Mapping variable of VPP construction to the Knapsack problem.

VPP Optimization Problem		Knapsack Problem
Join VPP Offer	Energy Price (P^i_{offer})	Item Value (v_i)
	Energy Amount (E^i_{offer})	Item Weight (w_i)
VPP Bid Request	Energy Demand (E_{demand})	Knapsack Maximum Allowed Weight (W)
	The reward for Energy Delivery ($Reward$)	Knapsack Minimum Allowed Value (V)
Binary decision variable ($\boldsymbol{\tau_i}$)		Binary Decision (x_i)

The optimization problem, in this case, is of type Pure Integer Non-Linear Program, due to the non-linearity of the objective function and binary values of the $\Gamma[i]$ array, contains linear and non-linear equations [38], [39]. We map the optimization problem to a variant of the decision problem of the Knapsack problem [40], which aims to determine the maximum value V that can be packed in a knapsack without exceeding the maximum allowed weight W of the knapsack (see Table 2).

The VPP construction optimization decentralization in a peer-to-peer energy trading network is inspired by the recursive implementation of a greedy algorithm for solving the Knapsack problem proposed in [41], [42] that either checks the solution with an item or discards the item and tries with a next item. This recursive implementation is suitable for blockchain decentralization where each prosumer acts as a node in the network, sends and receives joint VPP requests, and offers and finally creates a hierarchical structure of a root VPP like the call-tree of a recursive function. The following section will show the smart contract implementation of the proposed hierarchical VPP construction algorithm.

IV. BLOCKCHAIN AND SMART CONTRACTS

We have defined a public blockchain-based solution in which the small-scale prosumers are registered as peer nodes of the network and their monitored energy values are stored as energy transactions into the chain. Each prosumer is required to have an Ethereum node installed on-premises: either a full node deployed on a desktop computer or a light node deployed on a small single-board computer. The light nodes will only store headers of the blocks providing enough information to validate the consistency of the chain [43].

A prosumer has a smart contract that is associated with the smart meter and is used to manage in a decentralized manner the virtual aggregation and membership in VPP (see Figure 2). The contract will register the prosumer energy transactions on the chain, by signing them and then broadcasting them across the entire network. To enable this each prosumer must have a pair of public-private keys. The private key is used to sign the transaction, and the public key is used to generate the address that will pseudo-anonymously represent the smart energy meter in the blockchain network. This association and connection with the blockchain network are managed by the device on which the Ethereum node runs.

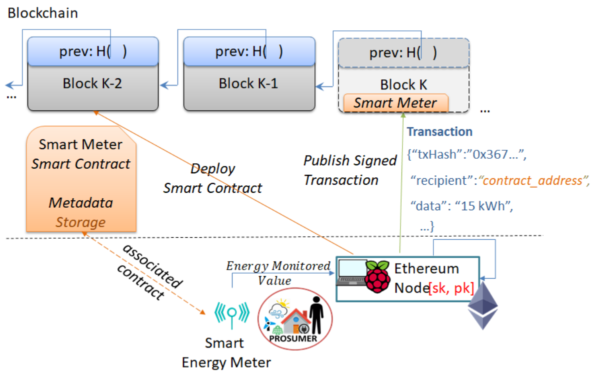

FIGURE 2. Ethereum node deployment and energy trasnactions registrion on blockchain.

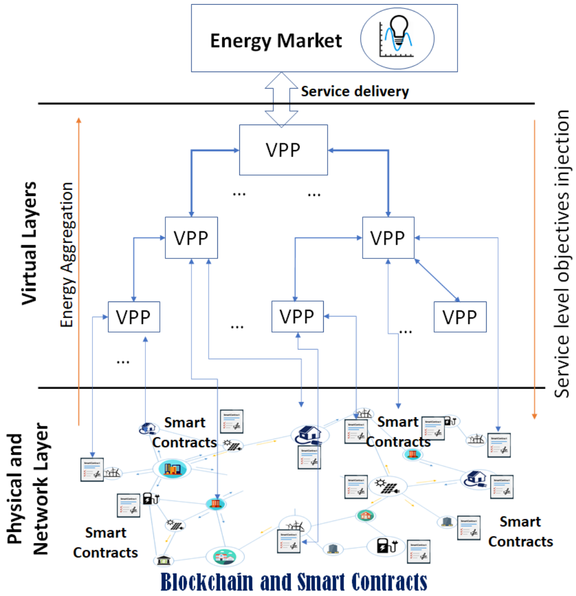

FIGURE 3. VPPs hierarchical structure.

We consider that each smart energy meter associated with a prosumer collects monitored energy data at each timestep $t \in T$. The device running the Ethereum node generates energy transactions aggregates the monitored energy values over an interval and signs the energy transaction with the private key. Consequently, the energy transaction will be signed with the prosumer's private key, while the recipient of the transaction is the smart contract associated with the smart energy meter.

The VPP is constructed incrementally following a hierarchical structure in which the VPPs on higher layers are built from other smaller scale VPPs or prosumers from lower layers (see Figure 3).

The Physical and Network Layer of the hierarchy will contain only prosumers which are the peer nodes in a blockchain graph, where the edges represent the connections among them. In terms of connectivity, it is a complete graph because all pairs of prosumers are connected using the distributed ledger feature of block replication in all network nodes. The layers on top will virtually aggregate them until a VPP fulfilling the energy service requirements is obtained at the root of the hierarchy.

Algorithm 1 Smart Contract Prosumer: New VPP Initialization

```
1:  Input: msg.sender and msg.value - blockchain variable used to identify the address signing the transaction and amount of Wei transferred; startTime and endTime - interval of the VPP construction; quantity - the amount of energy required by the new initiated VPP; price - the price per unit that the initiator is willing to pay; _vppGrid - smart contract state {INACTIVE, AUCTION, EXCHANGE}.
2:  Output: _vppGrid contract state is initialized to AUCTION; a request to join the VPP is sent to all prosumers.
3:  Begin
4:      require (msg.sender == prosumerContract)
5:      require (msg.value > price * quantity)
6:      require (_vppGrid.active == INACTIVE)
7:      _vppGrid.active = AUCTION
8:      _vppGrid.emptyProsumerList ()
9:      notifyAllProsumers (price, quantity, startTime, endTime)
10: End
```

The prosumers associated smart contracts aim at constructing Virtual Layers of VPP following a tree-like structure to fulfill the energy service level constraints while meeting the prosumers' local constraints. The prosumer will either become a member of an intermediary VPP or will initiate the construction of a VPP that will deliver the service.

Any prosumer can initiate the construction of a VPP for energy service delivery interval (see Algorithm 1). Anyway, a prosumer is not allowed to initiate the construction of more than one VPP for the same service delivery (lines 1 and 6). The main reason for imposing this constraint is the fairness of the process assuring equal chances for all prosumers in initiating and building a VPP. If more VPPs could have been instantiated by the same prosumer we may have ricked in a situation in which a wealthy prosumer may have the necessary tokens to dominate the VPP initiations processes by instantiating lots of new VPPs. This situation is commonly referred to as the "rich getting richer" problem. Also, there may be a case where a prosumer will want to create different hierarchies by publishing successive bids request with lower prices for the same energy service.

To initiate a VPP construction a prosumer smart contract will deposit tokens with the total amount that will have to be given to the potential VPP members for successful service delivery (see line 7). This acts as a security mechanism ensuring that it has a stake committed in the process and that at the end of the delivery session, the smart contract has the necessary money to pay the enrolled prosumers. The initiator generates a bid request notifying all the other peers that it is waiting for offers to join a new VPP (lines 7 and 9) and the managing contract state is changed to AUCTION.

Algorithm 2 Smart Contract Prosumer: Register Join VPP Offer

```
1:  Input: msg.sender and msg.value - blockchain variable used to identify the prosumer address and amount of Wei transfered in the transaction; quantity and price - quantity of energy the prosumer is willing to deliver, and the price unit.
2:  Output: _vppGrid - update contract state variable; adds the prosumer participant to the VPP.
3:  Begin
4:    require ($msg.value > price * quantity$)
5:    require ($\_vppGrid.sTime \leq cTime \leq \_vppGrid.eTime$)
6:    _vppGrid.pushBackProsumer(msg.sender, price, quantity)
7:    $newProsumer = \_vppGrid.getLastProsumer$ ()
8:    $sortP = OrderedByPriceDesc$ (_vppGrid.getProsumers())
9:    For each prosumer in sortP do
10:     If ($newProsumer.price < prosumer.price$) then
11:       swap (newProsumer, prosumer)
12:     End if
13:   End for
14: End
```

Algorithm 3 Smart Contract VPP: Energy Settlement

```
1:  Input: msg.sender - blockchain variable used to identify the VPP initiator address
2:  Output: _vppGrid – update state to EXCHANGE and returns the list of VPP prosumers
3:  Begin
4:    require ($msg.sender == prosumerContract$);
5:    require ($\_vppGrid.active ==$ AUCTION);
6:    require ($now > \_vppGrid.endTime$)
7:    $\_vppGrid.active =$ EXCHANGE; $vppEnergy = 0$;
8:    $maxEnergy = \_vppGrid.quantity$
9:    For each prosumer in _vppGrid.getProsumers() do
10:     prosumer.energySettlement()
11:     $vppEnergy += prosumer.quantity$
12:     If (currentVPPEnergy > maxEnergy) then
13:       partiallyMatch (prosumer, vppEnergy, maxEnergy)
14:       _vppGrid.matchParticipants.add (partiallyProsumer)
15:   Else
16:       _vppGrid.matchParticipants.add (prosumer)
17:   End if
18:  End for
19: End
```

The bid request is registered as a transaction on the blockchain. It contains the price per unit of energy, service constraints such as the amount of energy and interval for delivery, and the address of the prosumer smart contract that had initiated the VPP. The transaction signature is validated to ensure that only the transactions signed with the private key owned by the contract's owner are considered, thus preventing any malicious activity.

A prosumer may participate in the construction of several VPPs if it meets the constraints specified by the bid. To join a VPP a prosumer must respond with an offer that contains the energy service level values that it is willing to deliver (e.g. the amount of energy and price unit).

Upon receiving a join energy service offer from a prosumer, the smart contract of the VPP initiator validates that is meeting the request constraints (see Algorithm 2). If validation is successful, it registers the tokens deposit associated with the prosumer offer to secure its fairness in the trading process. Afterward, the contract registers the offer and adds the prosumer or smaller scale VPP to the list of members. Finally, it runs the energy rebalance algorithm to check if the VPP meets the requested energy service level constraints (lines 5-12).

The energy re-balance algorithm evaluates the state of the VPP each time a new offer for joining the VPP is registered. While the VPP is still accepting offers, its members are sorted in ascending order by their price per unit of energy, independent of the offered quantity, from left to right (cheapest price is the leftmost offer). When a new prosumer joins its service offer will be placed in the rightmost position. The more expensive offers are shifted to the left and an insert operation like the insertion sort algorithm is applied. Due to its simplicity and low complexity, this algorithm runs efficiently on the blockchain.

Algorithm 3 presents the energy settlement of the VPP construction process. At the end of the VPP construction interval (see lines 9-18) the root of the hierarchy will evaluate and finalize the construction session. When the VPP construction session finishes, the algorithm will return the first offers (from left to right) that can deliver the total amount of energy expected by the VPP. The list of members is determined by taking the first prosumers that sum the total quantity. The last prosumer's quantity of energy is split if the total sum is greater than the energy requested by the VPP (lines 12-14). The smart contract security validation can be seen on lines 4-6.

Finally, the actual delivery of energy is registered using prosumers associated smart meters and the financial settlement of prosumers accounts is conducted (see Algorithm 4). The smart contract is called only by the root of the hierarchy and will conduct the settlement recursively on all levels. Let's consider a prosumer acting as the initiator of a virtual layer $h-1$ in the hierarchy. The parent VPP smart contract from layer h will change its child VPPs state to INACTIVE enforcing them to conduct the energy and financial delivery check on layer $h-1$. The contract on level $h-1$ will change the state of all their children contracts on the $h-2$ level enforcing the settlement, and so on. When the calls reach the bottom level of the hierarchy the state of the VPP hierarchy will be sealed. Considering the actual monitored energy delivery values, the energy aggregation at virtual layers will be done in

Algorithm 4 Smart Contract VPP: Delivery Tracking and Financial Settlement

```
Input: msg.sender - blockchain variable used to identify the VPP initiator address.
Output: _vppGrid: the state is updated to INACTIVE; delivery of energy and financial settlement of prosumers wallets.
Begin
    require ($msg.sender == prosumerContract$)
    require ($\_vppGrid.active ==$ EXCHANGE)
    For each prosumer in _vppGrid.matchedProsumers() do
      prosumer.financialSettlement()
      If $prosumer.monitoredValues < prosumer.quantity$ then
        $diff = prosumer.quantity - prosumer.monitoredValues$
        prosumer.splitDeposit(diff)
      End if
    End for
    $\_vppGrid.active =$ INACTIVE
End
```

a bottom-up manner. Finally, the top-level VPP will start the financial settlement, which is done similarly by recursively invoking the smart contract method for every child node on all levels.

The interaction among smart contracts involved in a hierarchical VPP structure is depicted in Figure 4. We have considered the need for additional capacity from a BRP to deal with an imbalance in the day-ahead market. A prosumer tries to aggregate that energy by initiating the construction of the hierarchical VPP. The prosumer will become the initiator of VPP, the root of the hierarchical structure and will wait for offers from others to join. Using their smart contracts, other prosumers will publish join energy service offers during VPP construction sessions.

Based on the energy service requirements, all notified prosumers can compete for a place in the VPP hierarchy, either as individual prosumers or as part of new lower level VPPs. In both cases, a prosumer will offer a price per energy unit for an amount of energy it may deliver. If a prosumer decides to join as a part of lower-level VPP it will become an internal node of the network. If it opts to join individually, the prosumer becomes a leaf in the network.

Each offer received by a higher layer VPP level will trigger the energy rebalance to improve its member lists. The root VPP will stop the construction session by calling the energy statement function for each of its children nodes. The function will be called recursively at each layer of the hierarchy. All VPPs will evaluate the promised energy for each of their children until reaching the individual prosumers. The prosumers that had their offers rejected by their parent VPP will get the deposits back, while the prosumers with offers partially accepted will get a percentage of the deposit, equal to the percentage of the quantity of energy not matched.

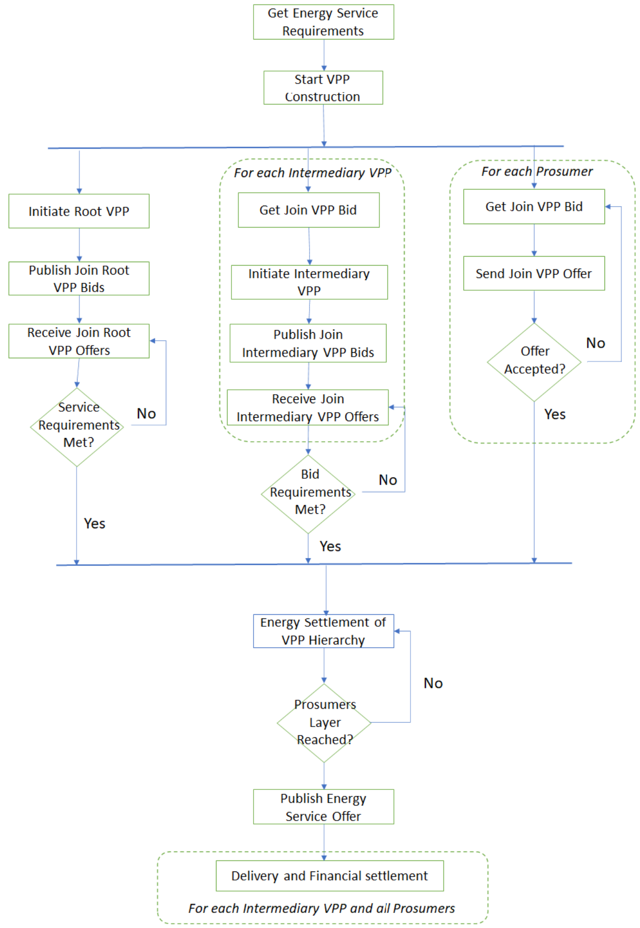

FIGURE 4. **VPP hierarchical structure construction process.**

After monitoring the prosumers' energy delivery, each parent VPP will conduct the settlement from a financial perspective. During the service delivery timeframe, each prosumer smart contract will track and register the monitored energy values (i.e. the actual amount of energy delivered). The monitored energy values will be registered as transactions in the blockchain. At the end of the delivery interval, they will be used by the parent VPP for paying the prosumers for the energy.

V. RESULTS AND ANALYSIS

To validate our blockchain solution for decentralized VPP construction and management we have implemented a proof of concept prototype using Ethereum [44]. The smart contracts have been implemented in Solidity and Ether (i.e. Wei subdivision) [45] was used as the coin for energy payments.

In our experiments, we have considered a set of small prosumers, their energy production profiles being taken from [46] which contains 4 years of data with a 15-minute sampling rate. The price per energy unit of energy requested by prosumers to join the VPPs is randomly generated in a

TABLE 3. Prosumers characteristics.

No. Prosumers	Quantity of Energy (kWh)		Energy Price per unit (10^14 Wei)
	Min	Max	
24	1	9	[1,10]
41	10	18	[1,10]
26	18	26	[1,10]

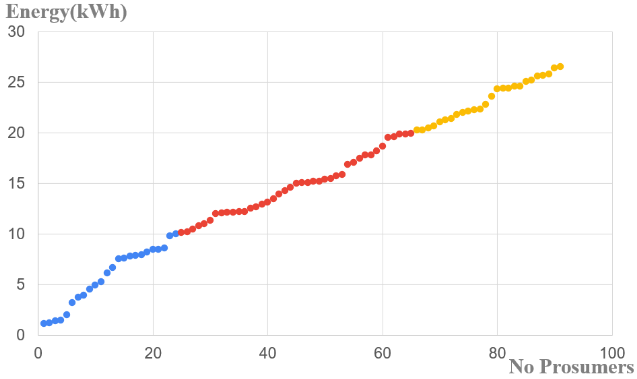

FIGURE 5. Prosumers clustering based on their energy profiles.

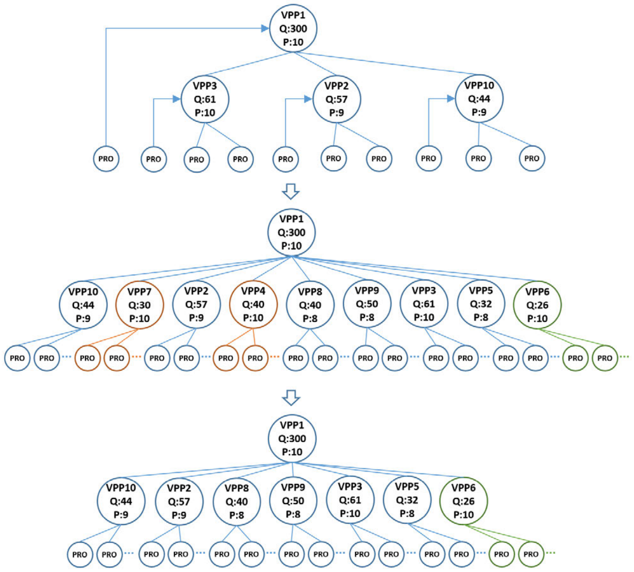

FIGURE 6. VPP structure successfully constructed to meet the request.

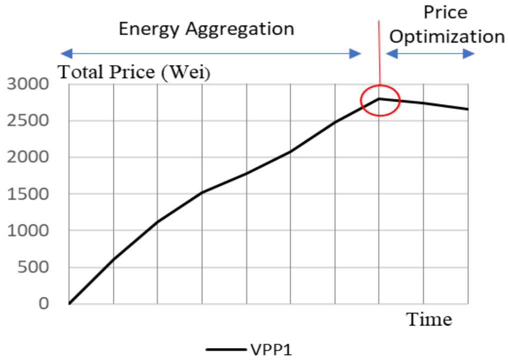

FIGURE 7. VPP construction main phases.

1-10 range of values. Table 3 presents the characteristics of the prosumers used in the validation process.

Figure 5 presents the prosumers' energy profiles clustered according to the total quantity of energy they may deliver. The colors are used to represent each of the considered clusters: blue prosumers with energy in the interval [1,9] kWh, red prosumers with energy in the interval [10,18] kWh, and orange prosumers with energy in the interval [19,26] kWh.

We have considered a scenario in which the BRP publishes a request for the energy of 300 kWh and 0,05 Euro /kWh (around 10^14 Wei) in the intra-day market with the deadline for submitting offers of 1 hour. No single prosumer can meet this request, thus, to deliver the expected amount of energy, the prosumers will need to be aggregated virtually in a VPP.

Several prosumers are initiating the construction of a VPP able to deliver the required amount of energy. Figure 6 presents the VPP structure that has been successfully constructed by running the prosumers associated smart contracts. For each new VPP in the hierarchy, the prosumer initiating the VPP publishes a request for a specific amount of energy (Q) and associated price for delivery (P).

In this case, reported the prosumer initiating the constructed VPP issues a bid request of 300 KWh at 10^14 Wei per unit. In parallel to this root VPP, other producers will initiate VPPs with smaller quantity requests.

The arrows show VPP initialization transactions by a prosumer and lines represent the join transactions between a VPP and its members.

The new offer will join the VPP and will replace the most expensive offers from the matched member list. VPP7 and VPP4 (marked with red in Figure 6) will be considered by the root VPP, due to their high price per unit and their offer request time, which was later than other VPP with same price per unit. VPP6 is selected as the highest priced matched offer. It will deliver just a percentage of its offer since the amount is greater than the remaining request-quantity that needs to be filled.

Each VPP in the hierarchy is responsible for managing its members. The offers to join are managed by sorting and rebalancing the VPP members to optimize the total energy price for energy. Although the prices are randomly generated, the VPP manages to integrate the prosumers optimally considering their price, even if the requests are sent unordered in the same mined block. In this way, the cost of energy service delivery is minimized if the AUCTION state of the corresponding contract is ACTIVE. Initially, the VPP has no members, so the total energy and price to be paid by VPP are 0. The total price will increase every time a new offer is received until the total quantity of energy is reached (i.e. Energy Aggregation phase in Figure 7). When the total amount of energy requested by the VPP is reached, the new offers registered are considered only if the price per unit is lower than of already matched offers (i.e. Price Optimization phase in Figure 7).

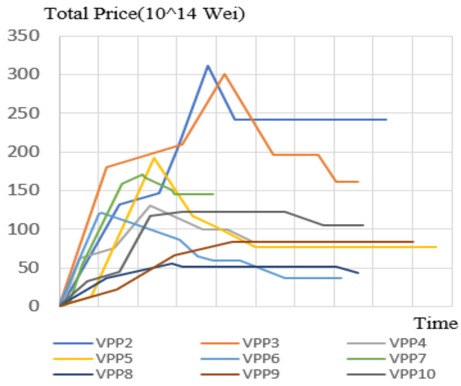

FIGURE 8. Total price evolution for intermediate VPP.

Figure 8 shows that the total price evolution follows the same pattern for all VPPs created in the hierarchy. When the energy demand is meet and the energy aggregation phase is over, new offers from prosumers will be considered only if they lead to a decrease in the total price (e.g. VPPs with ids 8, 9, 4, and 10 in Figure 8). In case the received offers are not better in terms of price than the ones already accepted in the aggregation phase, they will be refused, and the total price will remain constant (e.g. VPPs with ids 5, 9, 3, 7, and 2 in Figure 8).

Next, we have evaluated the lightness of our decentralized solution on the Ethereum public blockchain considering gas consumed and transaction throughput. Since the algorithm is entirely run by smart contracts, the scalability of the solution can be problematic on public blockchains, where the total gas used per block is limited by the network. Thus, we have compared our results with the public networks ones. In our experiments, we have considered the default configuration of the Ethereum Proof of Authority, having a 15 seconds block mining time and 11372093 gas limit per block [47].

The throughput of the blockchain system (transactions/block) is calculated as the maximum number of transactions to be included in a block. To determine this value for the energy transactions required for the VPPs construction the following formula has been used:

$$Throughput = (Block_{gasLimit} / TX_{gas}) \tag{26}$$

We have run scenarios with different hierarchical structures using the energy profiles of prosumers from [46]. We have varied several parameters like the number of layers in the hierarchy and the maximum number of members in a VPP. Table 4 summarizes the results obtained for each type of operation defined by our decentralized solution.

Figure 9 shows the transaction throughput and the gas consumption in case of having new prosumers joining a VPP. The smart contracts used to securely insert new join energy offers as transactions in the blockchain are only calling the smart contract of the VPP initiator thus the number of layers in the tree will not affect the gas consumed by the transaction.

Anyway, in terms of gas consumption, the prosumers, and VPPs on lower layers will pay the gas proportional to the size of the VPP they want to join. The enrolment with a VPP that already has 200 prosumers is feasible on the public blockchain in terms of transaction throughput, but the cost associated with the transactions will consume up to 1/5 of the total gas per block. At the same, it is independent of the number of layers in the VPP hierarchy because the parent VPP smart contract is the only one invoked. Thus, only the caller smart contract and the called contract will suffer a state update. Thus, a balance should be found between VPP hierarchical structure depth and the number of prosumers in the VPP for gas consumption minimization.

The energy settlement of the VPP hierarchy is dependent on the number of members in the intermediary VPPs and on the number of layers. The reason is the recursive calls necessary for stopping the AUCTION of each VPP smart contract from an intermediary layer and conducting the settlement. The throughput (i.e. number of transactions per block) for conducting the energy settlement of the VPP hierarchy is shown in Figure 10. Both the total number of members and the layers of the VPP network has been considered as variables.

The results are highly dependent on the height of the VPP structure, and on the number of members in the VPPs from intermediary levels. The throughput drops up to almost two transactions per block when the number of the prosumer in a VPP reaches 200 and the hierarchical structure has five layers. Although throughput is low at a maximum of 2

TABLE 4. Transactions throughput and gas consumption results.

Hierarchical Structure		VPP construction		Energy settlement		Financial settlement	
No VPP members	Height	Gas	Throughput	Gas	Throughput	Gas	Throughput
[0,50]	<4	445327	25.53	711704	15.97	2582422	4.40
[0,50]	>4	445327	25.53	1326627	8.57	2671403	4.25
[50,100]	<4	817233	13.91	1702007	6.68	6820180	1.66
[50,100]	> 4	817233	13.91	3128174	3.63	6958311	1.63
>100	< 4	1381337	8.23	2256268	5.04	10111429	1.12
>100	> 4	1381337	8.23	4131499	2.75	10254727	1.10

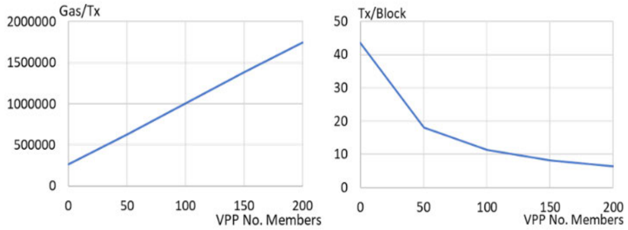

FIGURE 9. Join a VPP offer: Gas/Transaction (LEFT) and throughput (RIGHT).

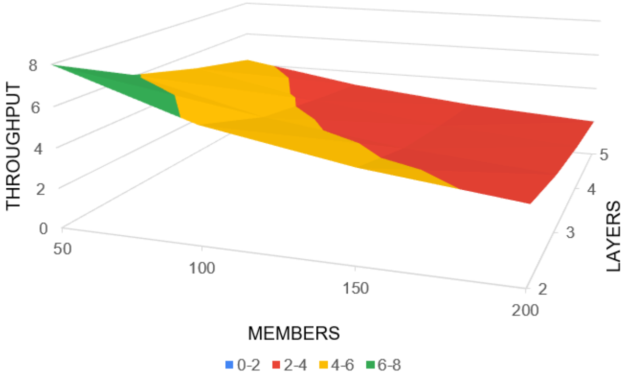

FIGURE 10. Energy settlement: transaction throughput variation with number of layers in in VPP hierarchy.

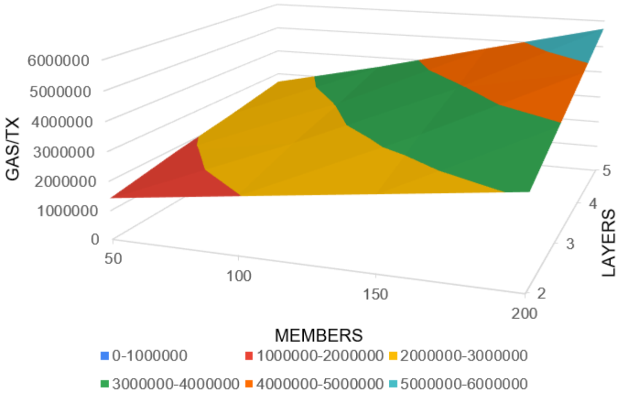

FIGURE 11. Energy settlement: gas consumption per transaction variation with number of layers in the VPP hierarchy.

transactions per block, this algorithm is called only once, after 1 hour for the VPP root initialization, so it will be securely registered on the blockchain.

Figure 11 shows, the energy settlement increases the transaction cost in terms of gas consumption linearly with both the number of members in VPPs and layers of the structure. However, in the case of energy settlement, the height of the tree is a critical variable for gas consumption.

In the case of energy delivery tracking and financial settlement, two types of functions are responsible to monitor the energy delivered by prosumers and making the necessary payments into their wallets. They are called by the smart contracts starting with the root of the hierarchy. As shown in Figure 12, the throughput, in this case, has lower dependability on the height of the VPP structure, but it has high dependability on the total number of prosumers in the intermediary VPPs.

When such a VPP reaches 150 members, the throughput is close to 1, which means that we reached the maximum number of members that an intermediary VPP can be sustained on a public blockchain such as Ethereum. Anyway, the allocation of prosumers in intermediary VPPs goes hand in hand with blockchain sharding mechanisms [48] which can be a solution for increasing the transaction throughput. In this case, the energy transactions among prosumers are isolated to the level of a shard delimitated by the membership in a VPP. The improvement comes because of introducing VPPs as clusters of prosumers responsible for the energy transactions. By splitting the energy transactions into different VPPs and parallelizing the validation and sealing of these transactions, higher transaction throughput is obtained.

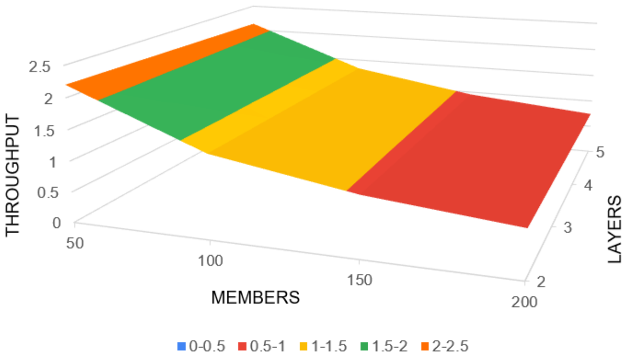

FIGURE 12. Financial settlement: throughput.

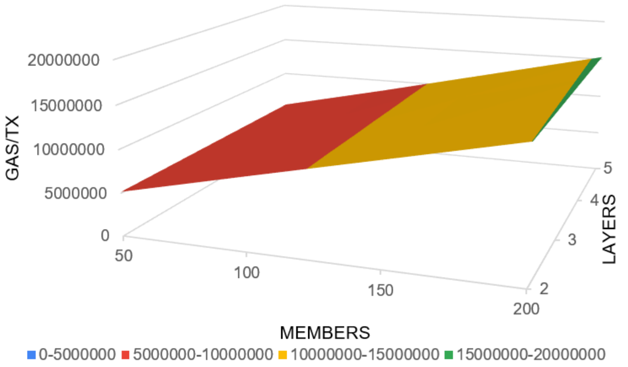

FIGURE 13. Financial settlement: Gas/Transaction.

Even though the overhead is significant, the financial settlement will be called once at the end of the delivery interval, so it is feasible to be run a public blockchain. As described, the height can change the gas consumption but with an insignificant amount compared to the number of members in the VPP. Another solution is to use a private deployment. In this case, the maximum amount of gas per mined block that needs to be set to support 200 prosumers in a single VPP with 5 layers is about16000000 gas (see Figure 13).

We have compared the proposed public blockchain-based solution with an edge-fog solution described in [46]. We evaluate the time needed to construct the VPP of the two solutions for several prosumers ranging from 5 up to 170.

In the first experiment, the execution time for constructing a VPP from a set of join offers that are placed simultaneously (see Figure 14). In the edge-fog solution, the VPP is constructed by solving a global optimization problem at the fog level needing all join offers from prosumers before starting the computation. Opposed to this, our decentralized solution computes the VPP structure iteratively building the hierarchical structure step-by-step as each offer is received

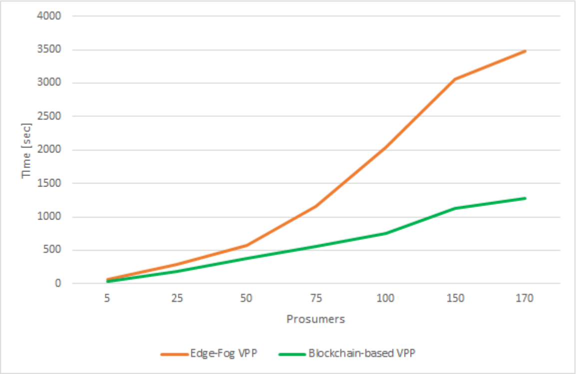

FIGURE 14. VPP construction runtime in case of simultaneous submission of prosumers join offers.

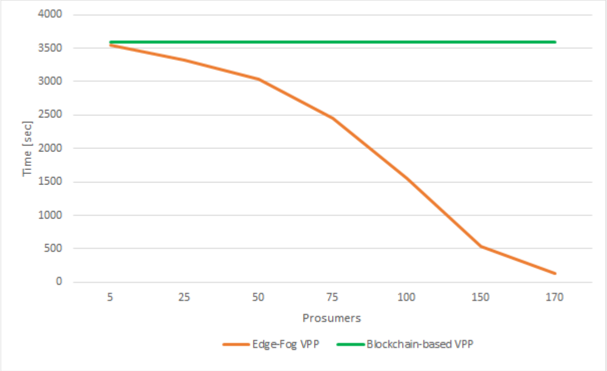

FIGURE 15. VPP construction runtime in case of even distribution of offers over a submission interval of 1 hour.

and the prosumer is added to the solution. The time needed to construct the VPP in a decentralized greedy manner is better than the time needed with a global solver.

The second experiment evaluates the impact of the even distribution of the join offers during an interval on the VPP construction runtime. Figure 15 shows that for the decentralized solution, if the prosumers place join VPP offers evenly over 1 hour, only 15 seconds are needed to generate a solution after the last join offer is sent, regardless of the number of prosumers involved.

This corresponds to the mining time of the blockchain block that contains the join offer transaction of the last prosumer. However, in the case of the edge-fog solution, the actual offering interval decreases continuously due to the increasing solving time of the global optimization problem, reaching around 5 minutes for 170 prosumers.

VI. CONCLUSION

In this paper, we proposed a public blockchain-based solution for constructing and managing VPPs of small-scale prosumers to meet energy services requirements. The VPP construction is iteratively and uses a hierarchical structure in which the VPPs on higher layers are built from smaller VPPs or prosumers from lower layers. The prosumers act as peer nodes of the public blockchain network and their monitored energy values are registered as transactions into the chain. A model of the VPP construction process has been introduced considering both prosumer land service level constraints and model decentralization is achieved using smart contracts. On the blockchain, smart contracts are used for implementing a lightweight version of the VPP construction process, energy delivery tracking, and financial settlement.

To validate our proposed solution, we have implemented a proof of concept prototype using Ethereum and we have used a data set of prosumers energy profiles. Reasonable values for transaction throughput and gas consumption are obtained. The results show the feasibility of the proposed solution on a public blockchain of up to 150 prosumers in a VPP in the hierarchy due to the high gas consumption of the financial settlement procedure call. For a higher number of prosumers, the sharding of the public blockchain should be considered following the hierarchical VPP structure and clusters of prosumers. Also, a private blockchain deployment may be considered. Even if the throughput of energy and financial settlement indicates a very high percentage of gas used inside a mined block, the minimum time interval for securely registering the energy transactions is much under the time between the actual calls of smart contract functions.

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