Tracing and Securing DER Transactions in the Wholesale Electricity Market using Blockchain

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***Abstract*—Participation of distributed energy resources (DERs) in the wholesale electricity market (WEM), provides an opportunity to DER owners to profit from dynamic energy prices and ancillary service products (ASPs) while enhancing reliability and flexibility of power systems. Recently announced FERC Order 2222 in the USA clarifies the regulatory rules to support this participation. The order directs the WEMs across the USA to accommodate the participation of DERs in the market through aggregators. This opportunity encounters two major challenges: (i) traceability of DERs service support by the aggregator, (ii) cybersecurity of the communications among the ISO, aggregator and DERs. To address these challenges, we propose a blockchain-based solution to assure traceability and security of energy/monetary transactions among different entities involved in this arrangement. First, we discuss what the ASPs characteristics of the aggregator-DERs engagement are. Next, we define the data that needs to be exchanged among the involved entities and how the energy, ASP and monetary transactions can be validated based on this data. Last, we discuss the blockchain framework design to preserve privacy, the consensus algorithm for transaction exchange, and data to be stored in the blocks.**

***Index Terms*-- Aggregator, ancillary services, blockchain technology, DERs, wholesale electricity market.**

I. Introduction

Distributed energy resources (DERs) play a key role in moving towards smarter grids, particularly by providing the opportunity to engage customers in the grid management processes. A particular type of DERs, which is receiving increasing attention nowadays, is nano-Grids (n-Grids). The n-Grids are smart buildings with on-site energy resources installed and owned by the consumers. These resources include, but are not limited to, battery energy storage system (BESS), photovoltaic panels (PV) electric vehicles (EVs), and controllable electric loads [1]. Although impressive advancement is observed in the technology and management strategies in order to make the n-Grids more profitable by balancing the building demand, e.g. the work done in [2], further studies are required for higher efficiency and profitability of these technologies.

There are many studies being conducted on the topic of transactive energy, peer-to-peer (P2P) trading and local electricity markets to take advantage of DERs [3]. However, deploying such systems widely faces high associated costs and the need for enhanced monitoring. One of the opportunities, which is receiving further attention after the announcement of Order 2222 of FERC, is to leverage the capacities of n-Grids and enhance their profitability is to participate through an aggregator in the wholesale electricity market (WEM) [4]. Since each aggregator may be aggregating thousands of DERs, particularly n-Grids, and each DER has multiple controllable energy resources, the tracing and securing the energy transactions is challenging. This arrangement requires tracing the aggregator response to the independent system operator (ISO) commands to dispatch the ASPs when needed, and securing the energy/ASPs/monetary transactions among the ISO, the aggregator and each DER.

The blockchain technology is well-known to improve the cybersecurity in the energy sector. However, its applications are majorly limited to P2P and local markets [5]-[8]. Authors in [5] proposed a uniform-price double auction electricity market whose real-time data exchange is performed in blockchain platform. The blockchain is also implemented to improve the cybersecurity and robustness of distribution grids [6]. In [7], blockchain is applied to microgrids for energy losses allocation. A comprehensive review on the applications of blockchain in the energy sector is provided in [8].

Taking advantage of the blockchain technology, we propose a solution for the use of the blockchain platform where all the transactions are securely recorded. This solution enables aggregators and DERs to record the ASPs offered by ISO, and in addition, ISOs, aggregators and DER owners can easily track the energy services offered by the market participants. We justify that a semi-private (consortium) blockchain platform equipped with proof-of-authority (PoA) algorithm is the best fit for this arrangement. We also demonstrate how the input data to be stored in the blocks can be deployed using the Ethereum platform [9].

The rest of the paper is organized as follows: Section II discusses n-Grid DER participation in the WEM using FERC Order 2222 for CAISO example, Section III gives an overview of blockchain technology. Section IV illustrates the challenges of tracing and securing the DER transactions and explores the proposed blockchain-based framework to overcome these challenges. Section V presents the data storage in the blockchain. The concluding remarks are made in Section VI.

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II. Participation of DERs in the WEM

A. A Closer Look at Order 2222 [4]

FERC Order No. 2222 defines DERs as generating units, energy storage systems or demand response programs typically in the range of 1-10 kW located in distribution system or behind the customer's meter. Our n-Grid fits this description. This order paves the way for the participation of n-Grids in WEMs through aggregators as new sources for energy and ASPs with minimum power requirement of 100 kW. By this order FERC expects lower costs for customers, enhanced grid flexibility and resilience and more competitive advancement in these technologies. Such an arrangement is shown in Fig 1.

The WEMs in the USA are similar in many aspects, but there are minor differences particularly in the procedure of running the market, defined ASPs and their requirements. We selected California ISO (CAISO) market structure since it appears ready for n-Grid to engage in demand side resources through an aggregator.

B. CAISO Wholesale Market Structure

The CAISO WEM is comprised of day-ahead market (DAM) and real-time market (RTM) [10]-[12]. In the DAM, the market participants submit hourly energy and ASPs bids for the 24 hours of next day. The ISO, based on the submitted bids and security and reliability requirements of the system, runs a cost minimizing optimization and determines the energy and ASPs of each participant. Two major processes in the RTM are real-time unit commitment (RTUC) and real-time dispatch (RTD). The participants are eligible to offer hourly bids in the RTM. Based on these bids, the ISO runs RTUCs with 15-min intervals. Between each RTUC, the ISO runs three 5-min RTDs. All the energy and ASPs trades in the DAM and RTUC are binding and the dispatchable participants must follow the orders of the ISO in the RTDs. The traceability and security of the orders is paramount to the operation.

The list of ASPs offered by CAISO is given in Table I [10]. Frequency regulation product is procured with the aim to maintain the system frequency at 60 Hz. The market participants, in order to be eligible for this product, must be equipped with the Automatic generation control (AGC) system. The dispatch timeframe for this product is ~4 seconds. The second product is spinning reserve product (SRP), mainly procured to respond to the system contingencies. The market participants must be synchronized to the grid and be able to deliver the energy under SRP in less than 10 min. The other main ASP is non-spinning reserve product (NSRP) procured to respond to contingencies, as well. For NSRP, the market participants must be able to synchronize and deliver the energy under NSRP in less than 10 min. Among the ASPs, we consider SRP as the best fit for the n-Grid DER aggregator to procure for the WEM due to the following reasons:

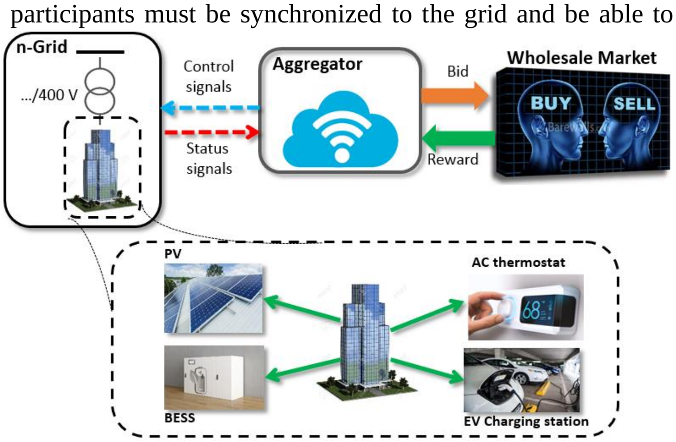

Fig. 1. The n-Grid/aggregator setup for participation is the WEM.

TABLE I
Features of ASPs Offered by CAISO

Type of ASP	Main purpose	Requirements	Time-frame
Frequency regulation	Maintain Freq. to 60Hz	Equipped with AGC	~ 4 Sec
Spinning reserve	Contingency Response	Sync. to Grid	< 10 min
Non-spinning reserve	Contingency Response	Be able to Sync. to Grid	< 10 min

- There is no need for AGC setup.
- Unlike frequency regulation, the aggregator has enough time to run a cost minimizer, self-scheduling optimization for its resources.
- The dispatch of SRP is much less frequent than the frequency regulation product.
- The marginal prices of SRP are higher than NSRP.

We consider 3 resources able to procure SRP in n-Grids, namely, BESS, EV charging station and air conditioner (AC).

C. Cybersecurity Attack Surfaces and Vectors

The communications among the n-Grids and the aggregator are done via internet of things (IoT), and therefore, this setup is highly vulnerable against cyber-attacks. The attack surface of the aggregator is its data center. The attack surfaces of the n-Grids are the sensors of "smart" resources of the buildings. They include controllers for the BESS, EV charging stations, rooftop PV, AC and the building smart meter. The attack surface of the ISO can be defined as its data center. However, we assume that the ISOs already have a protection set-up against cyber-attacks and we do not discuss it here.

The attack vectors for the n-Grids are: (i) the technical parameters, measurement signals and status of assets sent by n-Grids to the aggregator, (ii) the command signals sent by the aggregator to the n-Grids. In addition to (i) and (ii), the attack vectors of the aggregator are: (iii) the bids submitted to the WEM, (iv) the rewarded energy and ASPs received from the ISO and (v) the ASP dispatch signals received from the ISO.

III. An Overview on the Blockchain Technology

A. Improvement of Cybersecurity

The blockchain technology brings about multiple advantages. Every entity or node in the network have two keys: (i) public key which is perceived as the identity of the node, and (ii) private key which can be used to verify that the block is added by the node. Each block in order to be added to the chain will be assigned a particular "hash". Hash acts as the identity of the block and is automatically generated based on information of the hash of the previous block, the data stored in the block, the nonce, timestamp and the Merkle root's hash. Any change in a block after being added to the chain will alter its hash while the hashes of other blocks remain unchanged. Also, every node can connect to the network and download a copy of the blockchain which is automatically updated. This means that the data is scattered over the network and the process is decentralized. Using two keys for every node, the data becomes auditable since the sender signs the block with its private key and others can audit the block using sender's public key. The data in blockchain is transparent and time-stamped. The addition of blocks is totally automatic, meaning there is no human error. Last but not least, the blocks are verified by a network of computers based on particular consensus-based algorithms [13].

Blockchain improves the network security by data decentralization and human error minimization. Furthermore, an attacker, in order to tamper with a single block, needs to attack more than 51% of the nodes simultaneously and change the hash of all the previous blocks, which in a large population of n-Grids is nearly impossible [5].

B. Blockchain in the Energy Sector

The three main platforms to apply blockchain in are P2P energy trading, local energy markets, and WEMs. In the P2P platform, the agents trade energy directly. In local energy markets, the agents participate and trade their supply/demand over a specific area. The P2P and local energy market need complex considerations and investment to be implemented in practice. They are still under study and there is no widespread implementation of such platforms. On the contrary, the WEM platform is well-established and being used for a long time. Each platform can go totally on blockchain, or blockchain can be partially applied to certain processes of these platforms. These processes include, but not limited to, billing, real-time data exchange, grid management, and traceability [8].

As the ISOs facilitate the participation of DER aggregators in WEMs, one of the most critical challenges is tracing the source of energy transactions and ASPs offered by aggregators while recording transactions in a cyber-secure manner. We address this challenge by proposing a blockchain-based framework as described in the following Sections.

IV. Transaction Traceability Via Blockchain

A. The Blockchain Design

The blockchain platform can be public, private or consortium (also called partially private). The public blockchain allows anyone with internet access to become a node of the network and participate in the verification process. The public blockchain is the best option for a fully decentralized network. A permission is required to become a node in the private blockchain and one entity possesses the ownership and control of the network. The consortium can be counted as a hybrid of the public and private versions. The consortium blockchain brings about the following advantages:

- Permission to access the network is required and the identity of participants is known.
- Verification is performed by pre-determined nodes.
- It is much faster than public blockchain since the consensus is less demanding.
- Unlike public blockchain, it can be applied to highly regulated applications.
- It is semi-decentralized.
- Multiple entity ownership can prevent monopoly.

The aforementioned features make the consortium blockchain a highly suitable version for our case.

There are many consensus algorithms among which proof-of-work (PoW), proof-of-stake (PoS) and proof-of-authority (PoA) are worth mentioning. In the PoW, in order to validate a block, all the computers (miners) over the network compete to solve an automatically generated complicated puzzle and the one who solves the puzzle faster will be rewarded to validate that block. This algorithm needs a lot of energy, is very slow and highly vulnerable to 51% attack rule (i.e. if one has 51% of the mining power, it can manipulate the network). To overcome these challenges, PoS was introduced, which attributes the mining power of nodes (forgers) to their assets. With this algorithm, even if a node possesses 51% of the assets, it is not cost-beneficial to attack the network [14]. Nonetheless, the network will still be vulnerable to 51% attack rule. Lastly, in the PoA, the "reputation" of validators is at stake. In this algorithm, the number of validators is limited and their real identity is verified.

The PoW and PoS are useful for large public blockchains but they may not be useful in small size consortia. We find the PoA the best option for our use case for the following reasons:

- There is no need for sophisticated computers for transaction validation, i.e., low energy consumption.
- Fast transaction speed is assured since the block validators are selected pseudo-randomly and there is no competition among them.
- Each validator monitors the behavior of other validators to assure the security of transactions.
- Even if several validators are unavailable, the network can continue its normal operation.
- Tolerance to 51% attacks is achieved by the fact that the validators not necessarily possess the highest wealth or computing resources.

We select a PoA-based consortium blockchain for our application due the abovementioned reasons. Ethereum was determined to be the best platform to develop our framework since it is widely accepted, and highly flexible for custom applications and a PoA-based consortium [5]. It is worth mentioning that Solidity language is a proper choice for developing the underlying smart contracts.

B. Transaction Validation

The validation process of the procured energy and ASPs by aggregators is described next.

1) Aggregator/n-Grid interaction: We assume the n-Grids are equipped with the following meters/controllers:

(i) The building smart meter which sends the net-power of the building.

(ii) The BESS controller which sends the measured power output, the state of operation and the remaining SOC of the battery, and receives the power output and state of operation commands.

(iii) The EV charger controller which sends the connection of the EVs to the charging station, the measured power output, the state of operation and the remaining SOC of EV's battery, and receives the power output and state of operation commands.

(iv) The AC thermostat which sends the preset comfort range of building occupants, the measured power output, and the measured building temperature, and receives the building temperature command.

(v) The rooftop PV measured power output.

Note that (i) is mandatory for all n-Grids. If any of (ii)-(iv) is unavailable for a n-Grid, that resource is ineligible for SRP procurement. Lastly, (v) is optional and n-Grids may or may not be equipped with PV meters.

The three SRP resources of n-Grids are BESS, EV charging stations and AC. Based on (ii), the BESS technical constraints are given below [15]:

$$x_{i,t}^{b,m} = x_{i,t}^{b,c} \quad \forall i,t \tag{1}$$

$$p_{i,t}^{b,m} = p_{i,t}^{b,c} = p_{i,t}^{b,d} + (2x_{i,t}^{b,c} - 1)psr_{i,t}^{b,d} \quad \forall i,t \tag{2}$$

Where, sets *i* and *t* are for the BESSs and time-intervals respectively. We set time-intervals equal to 5 minutes. Superscript *b* indicates BESS, *m* measured signal by sensors, *c* command signal by the aggregator and *d*, desired values of the aggregator. p is the power output and psr is the portion of procured SRP summoned for energy generation. x denotes the state of operation. According to (1), the operating state of the BESS must match the operating state command sent by the aggregator where $x = 1$ denotes discharging state and $x = 0$ charging state. Based on (2), the measured power output of the BESS must match the power output command sent by the aggregator. The power output command corresponds to the desired power output and the summoned power under SRP. Note, $psr_{i,t}^{b,d}$ is added to $p_{i,t}^{b,d}$ in discharging state and subtracted from it in charging state (negative generation).

The measured signals at the terminal of BESS must abide its technical constraints enforced below:

$$x_{i,t}^{b,m}\left(p_{i,t}^{b,m} + sr_{i,t}^{b} - \bar{P}_i^{b,dis}\right) \le 0 \quad \forall i,t \tag{3}$$

$$\left(1 - x_{i,t}^{b,m}\right).\left(p_{i,t}^{b,m} - sr_{i,t}^{b}\right) \ge 0 \quad \forall i,t \tag{4}$$

$$\left(1 - x_{i,t}^{b,m}\right)\left(p_{i,t}^{b,m} - \bar{P}_i^{b,ch}\right) \le 0 \quad \forall i,t \tag{5}$$

$$psr_{i,t}^{b,d} \le sr_{i,t}^{b} \quad \forall i,t \tag{6}$$

$$soc_{i,t}^{b,m} - soc_{i,t-1}^{b,m} = \Big(\left(1 - x_{i,t}^{b,m}\right)p_{i,t}^{b,m}\xi_i^b - x_{i,t}^{b,m}p_{i,t}^{b,m}/\xi_i^b\Big).\Delta t \quad \forall i,t \tag{7}$$

$$\underline{soc}_i^b \le soc_{i,t}^{b,m} \le \overline{soc}_i^b \quad \forall i,t \tag{8}$$

$$(x_{i,t}^{b,m}.sr_{i,t}^{b}/\xi_i^b + (1 - x_{i,t}^{b,m}).sr_{i,t}^{b}.\xi_i^b).\Delta t \le soc_{i,t}^{b,m} - \underline{soc}_i^b \quad \forall i,t \tag{9}$$

$$p_{i,t}^{b,m}, p_{i,t}^{b,c}, p_{i,t}^{b,d}, psr_{i,t}^{b,d}, sr_{i,t}^{b} \ge 0\,; \quad x_{i,t}^{b,m}, x_{i,t}^{b,c} \in \{0,1\} \quad \forall i,t \tag{10}$$

The procured SRP is designated as sr. Superscripts dis and ch stand for discharging and charging states, respectively. Parameter $\bar{p}$ is the maximum power limits. soc, $\underline{soc}$ and $\overline{soc}$ stand for the current state of charge (SOC), minimum SOC and maximum SOC limits. Lastly, Δt shows the time-step and ξ the efficiency of BESS. According to (3), the available capacity of BESSs for SRP provision in discharging state ($x_{i,t}^{b,m} = 1$) is limited the available power capacity. In the charging state ($x_{i,t}^{b,m} = 0$), the BESS can be considered as a load (negative generator), and thus, the SRP capacity is limited to the current power output, as shown in (4). Enforcing (5), the charging power is greater than 0 only if the BESS is operating in charging state ($x_{i,t}^{b,m} = 0$). To assure that the dispatched energy under SRP does not exceed the procured SRP by the BESS, (6) is enforced. Constraint (7) ensures that the measured power aligns with the remaining SOC of the BESS. Based on (8) the SOC must remain between its minimum and maximum limits. The offered SRP by the BESS must not exceed the remaining SOC enforced in (9). Lastly, (10) ensures the power, SRP and power under SRP signals are positive and the status signals are binary.

Similar constraints apply to EVs. According to (iii), the only difference is that the chargers send availability signals to the aggregator. Hence, the following hold for $t \in T^{av}$ (T^{av} denotes the time intervals the EV is connected to the charging station):

$$x_{k,t}^{ev,m} = x_{k,t}^{ev,c} \quad \forall k \tag{11}$$

$$p_{k,t}^{ev,m} = p_{k,t}^{ev,c} = p_{k,t}^{ev,d} + (2x_{k,t}^{ev,c} - 1)psr_{k,t}^{ev,d} \quad \forall k \tag{12}$$

$$x_{k,t}^{ev,m}\left(p_{i,t}^{ev,m} + sr_{k,t}^{ev} - \bar{P}_k^{ev,dis}\right) \le 0 \quad \forall k \tag{13}$$

$$\left(1 - x_{k,t}^{ev,m}\right).\left(p_{k,t}^{ev,m} - sr_{k,t}^{ev}\right) \ge 0 \quad \forall k \tag{14}$$

$$\left(1 - x_{k,t}^{ev,m}\right)\left(p_{k,t}^{ev,m} - \bar{P}_k^{ev,ch}\right) \le 0 \quad \forall k \tag{15}$$

$$psr_{k,t}^{ev,d} \le sr_{k,t}^{ev} \quad \forall k \tag{16}$$

$$soc_{k,t}^{ev,m} - soc_{k,t-1}^{ev,m} = \Big(\left(1 - x_{k,t}^{ev,m}\right)p_{k,t}^{ev,m}\xi_k^{ev} - x_{k,t}^{ev,m}p_{k,t}^{ev,m}/\xi_k^{ev}\Big).\Delta t \quad \forall k \tag{17}$$

$$\underline{soc}_k^{ev} \le soc_{k,t}^{ev,m} \le \overline{soc}_k^{ev} \quad \forall k \tag{18}$$

$$(x_{k,t}^{ev,m}.sr_{k,t}^{ev}/\xi_k^{ev} + (1 - x_{k,t}^{ev,m}).sr_{k,t}^{ev}.\xi_k^{ev}).\Delta t \le soc_{k,t}^{ev,m} - \underline{soc}_k^{ev} \quad \forall k \tag{19}$$

$$p_{k,t}^{ev,m}, p_{k,t}^{ev,c}, p_{k,t}^{ev,d}, psr_{k,t}^{ev,d}, sr_{k,t}^{ev} \ge 0\,; \quad x_{k,t}^{ev,m}, x_{k,t}^{ev,c} \in \{0,1\} \quad \forall k \tag{20}$$

Set *k* stands for the EVs. One needs to notice that EVs only may procure ASPs during the times they are connected to the charging station. If bi-directional charger is unavailable, then $x_{k,t}^{ev,m} = x_{k,t}^{ev,c} = 0$.

The last resource of n-Grids eligible for SRP is AC. Based on (iv), this resource receives the temperature control signal from the aggregator ($\theta_{j,t}^{th,c}$) and sends the measured temperature ($\theta_{j,t}^{th,m}$) and measured power ($l_{j,t}^{th,m}$) to the aggregator. Thus, the following must hold:

$$y_{j,t}^{th,m} = y_{j,t}^{th,c} \quad \forall j,t \tag{21}$$

$$\theta_{j,t}^{th,m} = \theta_{j,t}^{th,c} = \theta_{j,t}^{th,d}(l_{j,t}^{th,d}, sr_{j,t}^{th,d}, psr_{j,t}^{th,d}) \quad \forall j,t \tag{22}$$

Here, set *j* indicates the ACs. y stands for the operating mode of the AC ($y = 1$: Cooling and $y = 0$: heating) and l is the average power output of the AC. According to (21) and (22), the operating mode of the AC and building temperature must match the corresponding signals received from aggregator.

The SRP procurement of the AC must abide the following:

$$l_{j,t}^{th,m} - sr_{j,t}^{th} \ge 0 \quad \forall j,t \tag{23}$$

$$l_{j,t}^{th} \le \overline{L}_j^{th} \quad \forall j,t \tag{24}$$

$$psr_{j,t}^{th,d} \le sr_{j,t}^{th} \quad \forall j,t \tag{25}$$

$$\theta_{j,t}^{th,m} - \beta_j\theta_{j,t-1}^{th,m} = (1 - \beta_j)(\theta_{j,t}^{amb} - y_{j,t}^{th,m}COP_j.R_j^{th}.l_{j,t}^{th,m}) \quad \forall j,t \tag{26}$$

$$\underline{\theta}_j^{th} \le \theta_{j,t}^{th,m} \le \overline{\theta}_j^{th} \quad \forall j,t \tag{27}$$

$$\beta_j \theta_{j,t-1}^{th,m} + (1-\beta_j)(\theta_{j,t}^{amb} - y_{j,t}^{th,m} COP_j . R_j^{th} . (l_{j,t}^{th,m} - sr_{j,t}^{th})) \geq y_{j,t}^{th,m} \overline{\theta}_j^{th} + (1-y_{j,t}^{th,m}) \underline{\theta}_j^{th} \quad \forall j,t \tag{28}$$

Parameter $\overline{L}_j^{th}$ stands for the maximum power limit of the AC. $\theta_{j,t}^{amb}$ denotes the ambient temperature, and $\underline{\theta}_j^{th}$ and $\overline{\theta}_j^{th}$ are the minimum and maximum allowable range of temperature set by the building occupants. Parameters β_j, R_j^{th} and COP_j are the building's thermal constant and thermal resistance, and the AC's coefficient of performance. β_j and R_j^{th} can be estimated using the recorded inside and ambient temperatures, and load of the AC, based on (26). As enforced in (23), the total SRP procured by the AC must not exceed the total power consumed by it which is consequently constrained to its maximum power limit in (24). The total power under SRP must not exceed the SRP of the AC per (25). Equation (26) gives the relationship of the inside and ambient temperature with the AC power and building thermal parameters. According (27) the building temperature falls into the range set by the occupants. Lastly, (28) assures if a portion of SRP is dispatched for energy, the building temperature does not exceed the comfort range of occupants.

2) Aggregator/ISO interaction: Regarding the interaction of the aggregator and the ISO, we consider the following:

(i) The aggregator submits day-ahead and hour-ahead energy and SRP bids to the ISO.
(ii) In the DAM, The ISO determines hourly energy and SRP amounts for the 24 hours of the next day.
(iii) In the RTM, firstly, the ISO determines 15-minute ahead energy and SRP amounts awarded to the aggregator in the RTUC process.
(iv) Secondly, in the RTD process, the ISO determines 5-minute ahead energy dispatch of the aggregator.
(v) Thirdly, whenever SRP capacity is needed for energy dispatch, the ISO must send the energy summon command to the aggregator in real-time.
(vi) The aggregator must demonstrate it abides the ISO commands by recording the energy dispatch and the capacity reserved for rewarded SRP in real-time.

If the aggregator does not bid in either of DAM or RTM, the corresponding energy/SRP rewards will be 0.

Therefore, according to the following, we can verify the validity of transactions between the aggregator and ISO:

$$E_{\lfloor (t-1)/12+1 \rfloor}^{dam} + E_{\lfloor (t-1)/3+1 \rfloor}^{rtuc} + E_t^{rtd} + PS_t = \sum_a p_{a,t}^{a,m} + \psi_t^e \quad \forall t \tag{29}$$

$$SR_{\lfloor (t-1)/12+1 \rfloor}^{dam} + SR_{\lfloor (t-1)/3+1 \rfloor}^{rtuc} = \sum_i sr_{i,t}^b + \sum_k sr_{k,t}^{ev} + \sum_j sr_{j,t}^{th} + \psi_t^{sr} \quad \forall t \tag{30}$$

$$PS_t = \sum_i psr_{i,t}^{b,d} + \sum_k psr_{k,t}^{ev,d} + \sum_j psr_{j,t}^{th,d} + \psi_t^{psr} \quad \forall t \tag{31}$$

$$0 \leq PS_t \leq SR_{\lfloor (t-1)/12+1 \rfloor}^{dam} + SR_{\lfloor (t-1)/3+1 \rfloor}^{rtuc} \quad \forall t \tag{32}$$

Where, E^{dam} and E^{rtuc} denote the rewarded energy in DAM and RTUC and E^{rtd} is the 5-minute energy dispatch command sent by the ISO. Likewise, SR^{dam} and SR^{rtuc} stand for the rewarded SRP in the DAM and RTUC. PS_t is the portion of SRP summoned by ISO for energy and $p_{a,t}^{a,m}$ is the measured power of n-Grid's smart meter. Parameters ψ_t^e, ψ_t^{sr} and ψ_t^{psr} correspond to the deviation of aggregator from the energy, SRP and power under SRP commands. Lastly, notation $\lfloor . \rfloor$ stands for the floor function (returning the greatest integer). Equation (29) verifies that the total energy rewarded by the aggregator plus energy under reserve, equals the total measured power of n-Grids and the associated deviation. Based on (30), the total rewarded SRP by the aggregator must match the procured reserve by its assets and the deviation. In (31) it is assured that the energy under SRP is supplied by the assets procured this ASP, which as enforced in (32) is limited to total SRP reward.

The payment for energy, SRP and energy under SRP to the aggregator for participation in the WEM is given in (33)-(35):

$$C_t^e = C_t^{e,dam} + C_t^{e,rtuc} + C_t^{e,rtd} - C^{e,pen} = E_{\lfloor (t-1)/12+1 \rfloor}^{dam} \lambda_{\lfloor (t-1)/12+1 \rfloor}^{e,dam} + E_{\lfloor (t-1)/3+1 \rfloor}^{rtuc} \lambda_{\lfloor (t-1)/3+1 \rfloor}^{e,rtuc} + E_t^{rtd} \lambda_t^{e,rtd} - \rho_t^e |\psi_t^e| \quad \forall t \tag{33}$$

$$C_t^{sr} = C_t^{sr,dam} + C_t^{sr,rtuc} - C^{sr,pen} = SR_{\lfloor (t-1)/12+1 \rfloor}^{dam} . \lambda_{\lfloor (t-1)/12+1 \rfloor}^{sr,dam} + SR_{\lfloor (t-1)/3+1 \rfloor}^{rtuc} \lambda_{\lfloor (t-1)/3+1 \rfloor}^{sr,rtuc} - \rho_t^{sr} |\psi_t^{sr}| \quad \forall t \tag{34}$$

$$C_t^{psr} = C_t^{ps} - C^{psr,pen} = PS_t . \lambda_t^{psr} - \rho_t^{psr} |\psi_t^{psr}| \quad \forall t \tag{35}$$

Where, C denotes payment, λ marginal price and ρ penalty factor. As can be seen, the payments are based on the traded amounts and the associated marginal prices, and penalties due to deviation from commands.

V. Data Stored in the Blockchain

Each block in Ethereum platform contains the following data: The block "Height" which shows the number of the block in the chain, the hash of the block, the amount internal currency of Ethereum used to compensate the block validators (depending on the agreement, we may assume 0 compensation for block validation), the public keys of the nodes which the data is sent from and received by, "Nonce" which shows the number of blocks generated by the node, and the input data generated by the block given in Bytes32 and Hexadecimal [5]. In the following, we elaborate on the input data needed from different entities for securely recording transactions. We assume no direct control or data exchange between the n-Grids and the ISO.

1) N-Grids to Aggregator: Each n-Grid generates every 5 minutes a block whose input data is given in Table II to securely record its assets' measurements and status. We defined notation ω to specify the asset whose data is stored in its corresponding row. For example, we can set: $\omega^s = 1, \omega^{pv} = 1$ and so on. For each n-Grid: if its PV is not equipped with a meter, the PV row will be removed. If its AC does not have a meter or the owner does not want to procure SRP from AC, its corresponding row will be removed.

2) Aggregator to n-Grids: The aggregator sends control signals to n-Grids every 5 minutes. As given in Table III, the aggregator only sends control signals to the controllable assets

TABLE II
INPUT DATA: N-GRIDS TO AGGREGATOR

Row	Data
Meter:	$\{p_{a,t}^{a,m}, \omega^{s}\}$
PV:	$\{p_{d,t}^{pv,m}, \omega^{pv}\}$
AC:	$\left\{COP_j, R_j^{th}, \beta_j, \overline{L}_j^{th}, \underline{\theta}_j^{th}, \overline{\theta}_j^{th}, \theta_{j,t}^{amb}, \theta_{j,t}^{th,m}, l_{j,t}^{th,m}, y_{j,t}^{th,m}, \omega^{th}\right\}$
BESS:	$\left\{\xi_i^b, \underline{soc}_i^b, \overline{soc}_i^b, \bar{P}_i^{b,dis}, \bar{P}_i^{b,ch}, soc_{i,t}^{b,m}, p_{i,t}^{b,m}, x_{i,t}^{b,m}, \omega^b\right\}$
EV CS:	$\{\xi_k^{ev}, \underline{soc}_k^{ev}, \overline{soc}_k^{ev}, \bar{P}_k^{ev,dis}, \bar{P}_k^{ev,ch}, soc_{k,t}^{ev,m}, p_{k,t}^{ev,m}, x_{k,t}^{ev,m}, \omega^{ev}\}$ ⋮

TABLE III
INPUT DATA: AGGREGATOR TO N-GRIDS

Row	Data
AC:	$\{\theta_{j,t}^{th,c}, \omega^{th}\}$
BESS:	$\{p_{i,t}^{b,c}, x_{i,t}^{b,c}, \omega^b\}$
EV CSs:	$\{p_{k,t}^{ev,c}, x_{k,t}^{ev,c}, \omega^{ev}\}$ ⋮

TABLE IV
INPUT DATA: AGGREGATOR TO ISO (BID)

Row	Data
Bid DAM	$\{\Lambda_{b,h}^{p,da}, P_{b,h}^{bid,da}, \Lambda_{b,h}^{sr,da}, SR_{b,h}^{bid,da}, L_{b,h}^{da}, h, \gamma = 1\}$ ⋮
Bid RTM	$\{\Lambda_{b,h}^{p,rt}, P_{b,h}^{bid,rt}, \Lambda_{b,h}^{sr,rt}, SR_{b,h}^{bid,rt}, L_{b,h}^{rt}, L_{b,h}, h, \gamma = 2\}$ ⋮

TABLE V
INPUT DATA: ISO TO AGGREGATOR

Row	Data
DAM rewards	$\{\lambda_h^{e,dam}, E_h^{dam}, \lambda_h^{sr,dam}, SR_h^{dam}, h, \gamma = 1\}$ ⋮
RTUC rewards	$\{\lambda_f^{e,rtuc}, E_f^{rtuc}, \lambda_f^{sr,rtuc}, SR_f^{rtuc}, f, \gamma = 2\}$
RTD results	$\{\lambda_t^{e,rtd}, E_t^{rtd}, \lambda_t^{ps,rtd}, PS_t, t, \gamma = 3\}$

of n-Grids. Here as well, if the AC is not controllable, its corresponding row will be removed.

3) Aggregator to ISO: The aggregator submits price-quantity energy and SRP bids for the 24 hours of DAM, on daily basis. In the RTM, the aggregator submits bids for the next hour. Every bid is comprised of multiple levels where each level includes the amount of product and the associated price. The blocks containing the aggregator bids need to contain data given in Table IV. Here, γ specifies the market the bid is submitted to ($\gamma = 1$: DAM, $\gamma = 2$: RTM). h denotes the hour and $L_{b,h}$ denotes the bid level. Parameters $P_{b,h}^{bid}$ and $SR_{b,h}^{bid}$ are the submitted amount of energy and SRP for level b at hour h, and $\Lambda_{b,h}^{p}$ and $\Lambda_{b,h}^{sr}$ are the corresponding prices. We will have $B \times 24$ rows for day-ahead bids, in which B is total number of bidding levels. In the RTM, we only have B rows since the aggregator only submits the bid for the next hour. Upon the market the aggregator is bidding to, it generates either a block with the data given in row 1 or 2.

4) ISO to Aggregator: The ISO sends two types of signals to the aggregator: (i) DAM and RTUC energy and ASP rewards, (ii) RTD dispatch and power under SRP commands. The input data of the ISO is provided in Table V. Note, upon the market process, the ISO generates the data of the corresponding row in this table.

VI. CONCLUSION

Participation of DERs in the wholesale market facilitated by FERC Order 2222 imposes several challenges to power systems, namely, cybersecurity of IoT based communications among the ISO, aggregator and DERs and tracing the sources of energy and ASPs provided by the aggregator. To address these challenges, we proposed an off-line blockchain-based platform to securely record the energy, capacity and monetary transactions in this scheme. We discussed that a consortium blockchain in which blocks are verified based on the PoA consensus algorithm is the best fit for our case. Further, we defined the data that needs to be stored in the blocks and how they can be used to verify the transactions.

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