Blockchain Implementation for DER Visibility and Transaction Verification in Wholesale Market

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***Abstract*—Distributed Energy Resources (DER), due to their high ramp rates, can bring about high flexibility and reliability to the power grid. A proper option to harness DER capabilities is their aggregation to offer ancillary service products (ASP) in the wholesale market. This option is backed by FERC Order 2222 requiring planning of the ISOs across the United States for participation of DER aggregators in the ASP markets. However, the DERs are spread across distribution grids which impedes tracking their ASP delivery. In this paper, we propose a blockchain-based framework to bring about the visibility of DERs to ISOs by secure recording and verification of the monetary, energy and ASP transactions made among the ISO, aggregator and DERs. Our major focus is on a type of DER named distributed prosumer (DP) which is comprised of rooftop solar generation, battery storage, electric vehicle charger and controllable electric loads. We conducted a case study where the simulation results demonstrate the accuracy and efficiency of the framework in making DERs visible and tractable to the ISO.**

***Index Terms*—Ancillary service product, blockchain technology, Distributed energy resource, visibility, wholesale market.**

I. Introduction

Distributed energy resources (DERs) are of a paramount significant for modern power systems. With an optimal management, they are poised to improve reliability, resilience and flexibility of the system operation, reduce carbon footprint, and increase the overall energy efficiency [1], [2]. A particular type of DER getting attention nowadays is the distributed prosumer (DP). A DP defined as a smart building equipped with rooftop photovoltaic panels (PV), controllable electric load, battery energy storage system (BESS), and electric vehicle (EV) charging station [3], [4]. The DP enables direct engagement of electricity consumers with the grid management and can be readily installed and used [5], [6]. However, the profitability of such technologies must improve to attract more customers to install them.

The DP can participate and offer multiple services in peer-to-peer energy trading schemes [7]-[9], retail distributed market [10]-[12] and wholesale electricity market (WEM) [13]-[19]. The latter brings about a great opportunity for higher profitability of DPs by offering dynamic energy pricing and participation in multiple ancillary service products (ASPs). This framework is receiving increasing interest after the US Federal Energy Regulatory Commission issued Order 2222 requiring the WEMs in the US to offer ASP procurement to DER aggregators [20]. A risk limiting model to offer optimal frequency regulation ASP in the market is proposed in [13]. A collaborative bidding model for DP aggregators is outlined in [14] where the uncertainties are captured through a scenario-wise ambiguity set. In [15], a demand response program is introduced using a coordinated stochastic decision-making algorithm. Flexibility ASP procurement by DP aggregators is discussed in [16], [17]. A bi-level optimization for DP aggregator participation in energy and SR markets is proposed in [18]. It was assumed the DPs can manage their own resources and the aggregator is a mediator between them and the ISO. Another bi-level optimization model for participation of DP aggregator in WEM to procure flexible ramping product was developed in [19]. It demonstrated the DP capability to offer its resources for WEM flexible ramping product procurement.

The literature mainly focuses on optimal bidding strategy models, whereas a major challenge that remains unaddressed is the visibility of DERs to the independent system operator (ISO). Since a single aggregator aggregates thousands DERs and DPs each of which has different resources that can offer ASPs, tracing the ASP source, verifying its service delivery and recording transactions must be addressed. Blockchain technology is a promising solution to the abovementioned challenges as it can record such transactions securely.

We implement the blockchain technology in the Ethereum platform to securely record and verify the data exchange among ISO, aggregator and DPs in order to verify the monetary, energy and ASP transactions. Our contribution is in the use of the proof-of-authority (PoA) as the consensus algorithm in a consortium (semi-private) environment since it fits the nature of the problem. We generated the transactions and blocks data in Python and used the Web3.py library to interface with a private Ethereum blockchain. Our implementation framework

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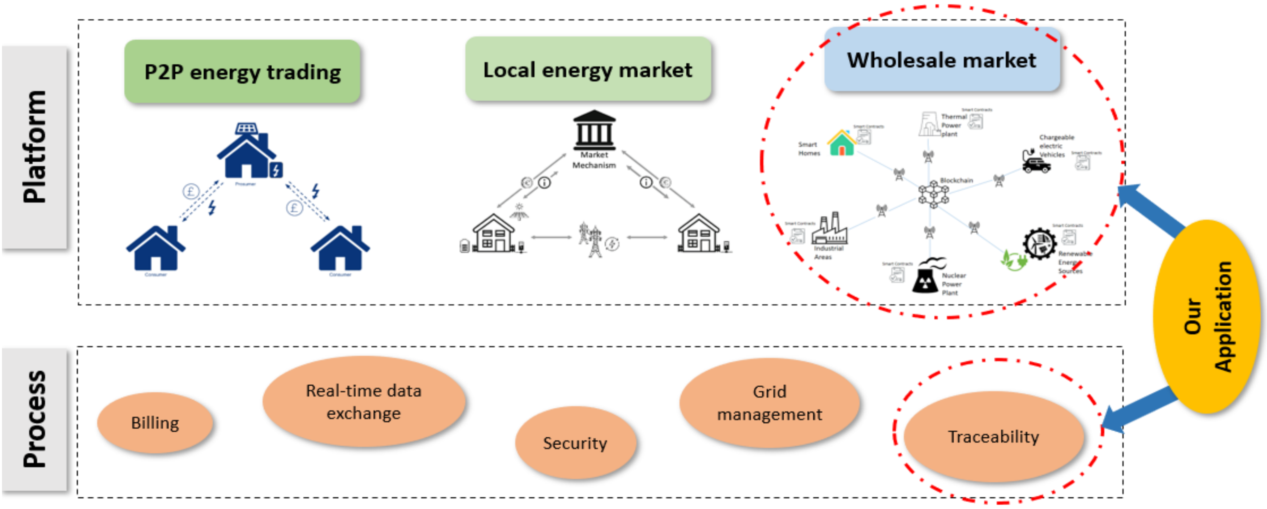

Figure 1. Blockchain Applications in the Energy Sector.

enables the ISO to trace the sources of ASPs and verify their delivery in real-time. The simulation results demonstrate the accuracy and scalability of the framework in this application.

The rest of the paper is organized as follows: A background on the benefits of the blockchain technology is given in Section II. The benefits of PoA consensus algorithm and consortium blockchain are outlined in Section III. The data to be recorded is presented in Section IV and the concluding remarks are provided in Section V.

II. Blockchain in the Energy Sector

The inherent features of the blockchain make it a secure technology for data recording [21]. It is a decentralized framework in which the data are scattered across a network of nodes (computers). The stored data are auditable, transparent and time-stamped (sequential). The transaction verification process is conducted automatically by a network of computers which causes minimized third-party interference. The updates are consensus-based and each block is associated with a hash which also contains the information of the previous block's hash. Any change in the block's data changes its hash while the other blocks' hashes are not affected (discrepancy). Each stakeholder can have its own copy of the chain which is updated automatically when a new block is added (distributed ledger). The intruder that aims at disrupting the recording needs to attack at least 51% of copies simultaneously which is near impossible [21], [22].

The blockchain technology contributes to a variety of advantages to the energy sector—see Figure 1. It can be implemented on different platforms, including (1) peer-to-peer energy trading where the DERs trade power directly, (2) local/retail energy markets where the DERs across a certain region participate in a retail market, and (3) WEM where the agents trade energy and offer ASP participation through an aggregator. These platforms can be totally operated with blockchain or it can be applied partly to some of the platform processes including customers billing, real-time data exchange, cybersecurity, grid management and traceability of the services.

Although the blockchain technology has many advantages, it introduced some challenges, too [23], [24].

- Storage requirements: one needs to download all the data to validate transactions.
- Transaction speed: only a limited number of transactions per second can be performed.
- Accuracy and reliability of data: If bad data are offered correctly, they will end up on a blockchain, i.e., only authenticity is ensured.
- Security issues: creating secure blockchain frameworks requires expertise and the blockchain may be still vulnerable to cyber-attacks.

III. Blockchain Features in Our Application

Two major features of the blockchain framework to be chosen are the privacy and consensus algorithm. In the following, we discuss how we have implemented the options, and what advantages they bring to the WEM APS management.

A. Privacy

The blockchain can go totally public, that is, any person can be connected to it and have a copy of transactions. It can also go totally private where it is owned by a single entity and permission is required to connect to the network. Another variation is the consortium (semi-private) option, which has the features of a private network but under multiple ownership [21]. The consortium option fits our application the most due to the following features:

- Permission required,
- Faster than the public blockchain,
- Multiple entity ownership,
- Participants are known,
- Ability to apply PoA consensus algorithm,
- Limited decentralization.

B. Consensus Algorithm

There are a variety of consensus algorithms each of which fits a particular application [24]. The major ones broadly implemented are proof-of-work (PoW), proof-of-stake (PoS) and proof-of-authority (PoA). The PoW is too energy consuming since the miners need powerful processors in order to compete over solving a randomly generated problem where the one with the best solution is awarded to verify the blocks. Hence, sophisticated software is needed. The PoW is implemented in Bitcoin. In the PoS, the miners validate the blocks based on the amount of coins they possess. The PoS is used in Altcoin. A challenge of PoS is that the stakeholder with higher stakes can mine much easier than others and can vote for both forks of the blockchain, i.e., when the blockchain diverges in two potential paths forward and one must be voted for. On the other hand, in the PoA, the validators need to identify themselves to be able to mine, which means their reputation is at stake [24]. The PoA algorithm fits our application due to the following features:

- No need for high performance computing platform,
- Tolerance to 51% attack rule,
- Pre-approved validators,
- Reputation over possession,
- Faster than others,
- Limited number of validators.

IV. Data Storage

The blocks in the Ethereum must contain the following specifications [21]:

- Height which indicates the number of the new block in the blockchain.
- Block Hash which can be perceived as the identity of the block which is cryptographically derived from the blockchain data.
- The value of Gas (internal currency of Ethereum) to compensate the network validators (miners).
- The public key (ID) of the nodes sending and receiving the block data.
- Nonce which denotes the total number of blocks submitted by the sending node.
- The input data in Bytes32 and Hexadecimal.

The aggregator functions as the mediator between the ISO and DPs is shown in Figure 2. The market has 3 major processes: day-ahead market (DAM), real-time unit commitment (RTUC) and real-time dispatch (RTD). The aggregator may submit energy and ASP bids to the DAM and RTUC and the ISO sends the cleared amounts and prices back. In the RTD with 5-min time steps, only the ISO sends dispatch commands to the participants [25]. The aggregator directly manages the DP resources by sending control signals to DPs and receiving status and measurement signals from them. In the following, the data storage requirements are presented.

1) Aggregator to ISO: The aggregator submits daily energy and ASP bids to participate in the DAM. Then, it has the option to submit hourly bids in the RTM. The bids contain

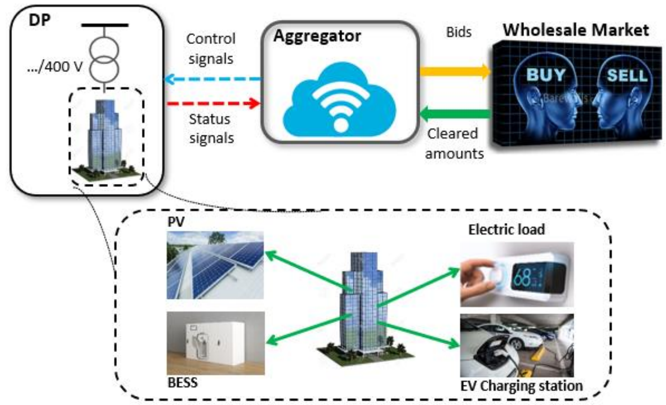

Figure 2. ISO/Aggregator/DP interactions.

price and quantity for energy and ASP. Table I shows the aggregator to ISO data exchnage to be stored in the blockchain. The bids to the dam contain 24 rows for 24 hours and bids in RTM contain only 1 row. Also, γ shows the market where $\gamma = 1$ means DAM and $\gamma = 2$ is RTM.

2) ISO to Aggregator: The ISO sends the cleared amounts of energy and ASPs participation along with the marginal prices to the aggregator. All of these transactions are binding. On this basis, the ISO sends to the DAM cleared results every 24 hours, the RTUC cleared results every 15 min, and the RTD dispatch results every 5 min. The ISO to aggregator data storage is given in Table II. Note, $\gamma = 3$ indicates RTD here.

*3) Aggregator to n-Grids:*The aggregator only sends the control signals to the n-Grid resources in order to meet the energy and ASP requirements. In a normal operation mode, these signals are sent every 5 min. In case of emergency, if the ISO calls for ASP activation, the aggregator sends control signals immediately. The aggregator to n-Grid data exchnage storage is provided in Table III.

4) N-Grids to Aggregator: n-Grids must send the status and measured power output of each resource to the aggregator. These data are recorded for verification of energy and ASP transactions. The timeframe of data recording is 5 min unless

TABLE I
DATA: FROM AGGREGATOR TO ISO

Row	Data
Bid DAM	$\{\Lambda_{b,h}^{p,da}, P_{b,h}^{bid,da}, \Lambda_{b,h}^{sr,da}, SR_{b,h}^{bid,da}, L_{b,h}^{da}, h, \gamma = 1\}$ $\vdots$
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 II
DATA: FROM ISO TO AGGREGATOR

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

TABLE III
DATA: FROM 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:	$\{p_{k,t}^{ev,c}, x_{k,t}^{ev,c}, \omega^{ev}\}$
	$\vdots$

TABLE IV
DATA: FROM N-GRID 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:	$\left\{\xi_k^{ev}, \underline{soc}_k^{ev}, \overline{soc}_k^{ev}, \bar{P}_k^{ev,dis}, \bar{P}_k^{ev,ch}, soc_{k,t}^{ev,m}, p_{k,t}^{ev,m}, x_{k,t}^{ev,m}, \omega^{ev}\right\}$
	$\vdots$

the n-Grid resources are called up for ASP activation. The data to be stored is represented in Table IV.

In [4], we discussed how the stored data in the blockchain can be used for transaction verification, ASP delivery and monetary payments.

V. CASE STUDY

The blockchain setup is depicted in Figure 3. Python program where all the transactions and data exchanges occur can talk to the blockchain through a remote procedure call (RPC) encoded in JSON (JSON-RPC). Web3.py interface enables developing clients that interact with the blockchain network [26]. Each node in the Ethereum network is represented by an Ethereum virtual machine (EVM). Each EVM client can generate blocks, download and read the data in the blockchain. The Ethereum network is developed in Go Ethereum (Geth) implementation [26]. The simulations are developed in Windows 10 operating system on a PC with 2GB SSD hard drive, 64GB RAM, 8 cores and 16 logical processors (CPU threads). We consider 200 agents (DPs) which through the aggregator participate in the energy and spinning reserve markets. The data of agents and the market are given in [18]. We assume the DP aggregator participates in the WEM aiming to trade energy and procure spinning reserve product (SRP).

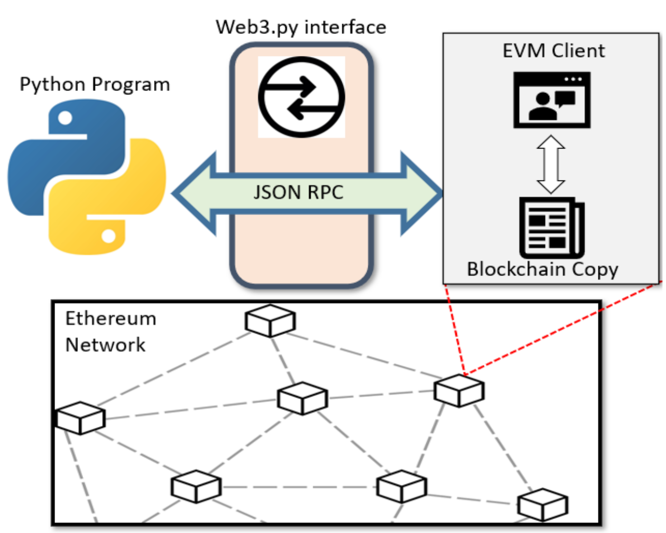

Figure 5. The Ethereum blockchain setup.

The time needed for generation, validation and sealing of 10 transactions versus the number of miners and the number of CPU threads (logical processors) in our case study is given in Table V. As it is observed, the processing time is the lowest when the number of miners is 3. Higher number of miners require more processing power causing higher processing time. Lower number of miners increase the processing time, as well, since they need to validate blocks one by one. Furthermore, as the number of CPU threads employed for Ethereum network increases (higher processing power), the block validation time decreases. Note, even though all the mining work is performed on a single PC, the block generation and sealing time is not significant. Hence, it will not impact the performance of the blockchain in real cases where a large number of computers are connected to the blockchain network.

TABLE V
TIME NEEDED FOR VALIDATION OF 10 BLOCKS

	2 Miners	3 Miners	5 Miners	10 Miners
4 CPU threads	66.3 s	42.1 s	44.4 s	48.7 s
8 CPU threads	42.8 s	32.0 s	35.1 s	42.6 s
16 CPU threads	31.8 s	25.5 s	32.1 s	37.8 s

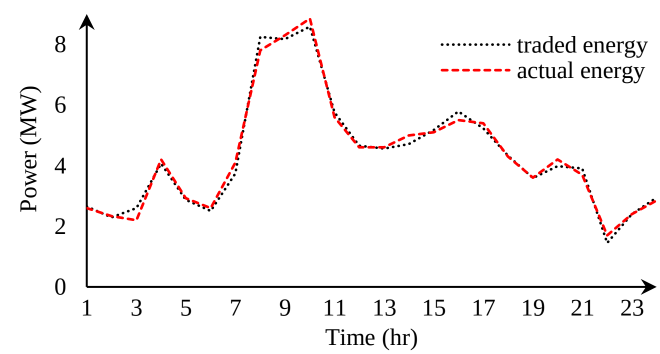

Figure 4. The traded and actual energy consumption of DPs.

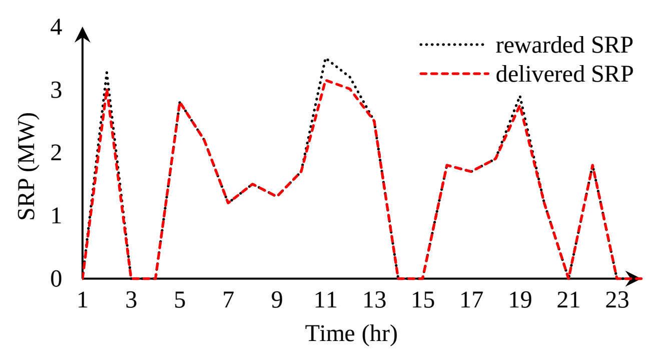

Figure 3. The rewarded and delivered SRP by the aggregator.

The energy traded in the market versus the actual energy of the DP aggregation obtained from the stored data in the blockchain is provided in Figure 4. As shown, there are discrepancies between the two which if not detected may result in imprecise performance and profit loss of the aggregator in the WEM. The rewarded SRP and the actual SRP delivered in real-time are depicted in Figure 5. The aggregator was unable to deliver the rewarded SRP at hours 2, 11, 12 and 19. The inability to deliver SRP in real-time imposes serious penalties to the aggregator. Besides, it may jeopardize the ability of the ISO to respond to contingencies as the exact amounts of SRP required for secure operation of the system are not delivered in real-time. The issue of DP resource availability will become more challenging as the number of DER aggregators increases. The developed blockchain framework brings about the visibility of the DERs, which intend to participate in the WEM, to the ISO. It is of a vital significance since their traded energy and ASPs may deviate from the actual amounts in the real-time, which causes improper operation and affects (reduces) monetary compensations to the stakeholders.

VI. Conclusion

The DPs are a key component to power grids which improve the flexibility, resilience and reliability of the system. A viable approach is to harness DPs high ramp capacity in ASP procurement for the wholesale market. The DPs are connected to the distribution grid and their visibility and transaction verification is a challenge for the ISO. Our work demonstrates:

- How a blockchain-based framework can be used to record energy, ASP and monetary transactions securely, which can be later used for transaction verification, and energy and ASP delivery.
- How the framework is developed in the Ethereum platform using PoA consensus algorithm. The transactions are generated in Python and Web3.py library enables interface with a private Ethereum blockchain.
- The applicability and scalability of the framework where high number of transactions can be validated in a short period of time. We illustrate that the DPs (in our case study) may not be able to deliver the exact amounts of the rewarded ASPs in the real-time which may jeopardize secure operation of the power grid.

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