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A Blockchain-Enabled Multi-Settlement Quasi-Ideal Peer-to-Peer Trading Framework

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***Abstract*—The concept of peer-to-peer (P2P) trading, or transactive energy (TE), is gaining momentum as a future grid restructure. It has the potentials to utilize distributed energy resources (DERs), proactive demand side management (DSM), and the infusion in information and communication technologies (e.g., blockchain and internet of things (IoT)) for promoting the technical and economic efficiency of the system in its entirety. An efficient market framework is vital for the successful and sustainable implementation of such a concept. This paper proposes a P2P energy trading framework enabled by blockchain. It consolidates bilateral contracts, an electronic-commerce platform, a double-auction Vickrey-Clarke-Groves (VCG) mechanism, and trading functionalities with the main grid. Through these multi-layer mechanisms, various trading preferences and attributes of electricity generation and/or consumption are accommodated. Meanwhile, the VCG mechanism eliminates any potential for market power exercise via incentivizing truthful bidding of participants. Different remedies are proposed to overcome the drawback of VCG, i.e., the lack of balanced-budget property. Accordingly, the proposed trading framework is described as multi-settlement and quasi-ideal. Case studies are conducted to analyze and evaluate the proposed trading framework and demonstrate the effectiveness of the proposed remedies in handling probable market deficiencies.**

***Index Terms*—Blockchain; electricity markets; energy community; energy trading; peer-to-peer energy trading; transactive energy; Vickrey-Clarke-Groves.**

I. Introduction

THE peer-to-peer (P2P) paradigm is a future trend/evolution in the restructuring of electric power systems [1]-[4]. It is primarily driven by distributed energy resources (DERs), proactive demand side management (DSM) (facilitated by smart appliances such as distributed energy storage (ES), electric vehicles (EV), and controllable loads (CLs)), and emerging information and communication technologies (e.g., blockchain and Internet of Things (IoT)). It facilitates an environment in which different agents/peers (e.g., "prosumers" or consumers with production and/or storage capabilities) can conduct mediator-free electricity transactions (i.e., buy and sell) with other peers in the system.

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The P2P paradigm is also referred to as transactive energy (TE), which is defined by the GridWise Architecture Council as a system of economic and control mechanisms that allows the dynamic supply-demand balance across the electric power infrastructure using value as a key operational parameter [5]. It is anticipated that by 2026, the P2P platforms will create a revenue of more than $4 billion US dollars [6].

The implementation of a P2P paradigm mandates an information and communication infrastructure that integrates different peers in a simple and effective way to communicate and conduct transactions. Recent years have witnessed the rapid development of IoT technology in the smart grid through both wired and wireless communication protocols (e.g., smart home automation system, Internet of EV chargers). This is leading to the transition of the power grid from one-way to two-way ubiquitous interconnections, enabling millions of distributed resources to participate in grid operations and energy trading in a P2P manner. Blockchain, which offers auditability, immutability, privacy, security, and the capability to provide device/peer-level trust, has gained significant attention as a promising technology to underpin decentralized P2P platforms. The decentralized architecture of blockchain has made it a suitable solution to integrate IoT-enabled distributed resources in the P2P market and to ledger the trustable contribution of participants. Moreover, the capability of implementing smart contracts allows the automatic execution of trading agreements, thus facilitating a smarter and more reliable P2P market.

As a pivotal ingredient for the success of the P2P paradigm, different P2P energy trading mechanisms have been proposed and discussed in the literature; they include auction-based mechanisms [7]-[10], bilateral-contract-based mechanisms [11], [12], and game-theoretic-based models [13]-[15]. A P2P mechanism for joint energy and uncertainty trading based on a single-sided auction is proposed in [7] to match the uncertain power generation with flexible loads locally. An auction-based P2P platform for energy trading based on various heterogeneous attributes of electricity (e.g., generation source, location, and reputation) is discussed in [8]. A P2P model for energy trading of crowdsourced energy systems in day-ahead and hour-ahead auctions that account for transmission losses is discussed in [9]. An auction-based TE control mechanism for networked microgrids that accounts for grid constraints and implements locational marginal pricing is developed in [10]. A scalable bilateral contract networks for P2P energy trading in forward and real-time markets are proposed in [11]. A framework for P2P energy trading based on multi-bilateral economic dispatch with product dif-

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ferentiation based on various energy attributes is discussed in [12]. A Stackelberg game, with producers/consumers act as leaders/followers, is formulated in [13] to model the energy trading interactions among peers in virtual microgrids. The energy management via P2P transactions in a building cluster is modelled as a two-stage strategy in [14], where the market clearing is determined in the first stage based on the total social energy cost minimization and a non-cooperative game is implemented in the second stage to determine the clearing prices. A Stackelberg game is proposed to model the P2P energy trading among prosumers in a community microgrid in [15], where the sellers compete in price and the buyers, competing in seller selection, adjust their energy consumption based on the prices and quantities of energy offers by sellers.

To the best of authors' knowledge, most (if not all) of the P2P trading frameworks in the literature have ignored the simultaneous satisfaction of various participant preferences in the trading of different types of electric sources/demands, and the possibility of market manipulation via the exertion of market power. The latter is a key weakness that jeopardizes the success and sustainability of a newly introduced P2P paradigm which has higher potential, compared to well-established wholesale markets, to experience market manipulation and/or few market participants, at least in its early stages of implementation. As an attempt to overcome the aforementioned drawbacks, this paper proposes a multi-settlement P2P trading framework enabled by a consortium blockchain ledger system. This framework consolidates four trading mechanisms: 1) bilateral contracts, 2) electronic-commerce (e-commerce) platform, 3) double-auction Vickrey-Clarke-Groves (VCG) mechanism, and 4) trading with the main grid). It accommodates diverse trading preferences, eliminate any potential for market power, and attain immunity against collusion and shill bidding. The VCG mechanism incentivizes participants' truthful bidding, eliminates market power, and maximizes the social welfare [16]. The balanced-budged property of the double-auction VCG mechanism, which is the only missing property to attain the mechanism's ideality, is fulfillable, at least partially, via various proposed remedies, including a novel balanced-budget VCG pricing rule. The immunity to collusion is provided by the existence of four parallel trading mechanisms. In the meantime, a proof of clearance (PoC) mechanism is designed and incorporated with the VCG mechanism to manage the digital identity of participants and accordingly provide immunity to shill bidding, execute the consensus process of the trading, and update the blockchain ledger. Accordingly, the proposed framework is described as a multi-settlement and quasi-ideal trading framework.

Single-sided VCG auctions have been applied to wholesale electricity markets [17], [18], demand management [19], [20], and energy procurement in a decentralized TE-based system [21]. A modified VCG double-auction mechanism is applied to determine the optimal allocation and prices for the ES sharing framework, as discussed in [22]. In contrast, this work is the first, to the best of the authors' knowledge, to propose a double-auction VCG mechanism for blockchain-based P2P energy trading with remedies for its lack of the balanced-budget property. Meanwhile, compared to the blockchain application in existing energy trading frameworks, the proposed PoC provides a high consensus efficiency by avoiding the accumulating computation burden and the blockchain fork issue found in the energy-consuming proof of work (PoW) (e.g., [23]-[25]) and proof of stake (PoS) (e.g., [26]) algorithms. In addition, both PoW and PoS are designed for public blockchain application, which lacks the membership/identity authorization and may not be directly used in consortium blockchains such as the proposed case.

The deployment of blockchain in these systems, especially the consensus processes, are separated from the trading mechanisms, which lacks the consideration of the trading peers' motivation in managing the blockchain. This may also result in potential security issues. For example, the hyperledger fabric network (HFN) technique, deployed in [9], uses a separate cloud server, and in turn is vulnerable to single-point failure via attacks on the cloud server or communication.

The main contributions of this paper include the following: 1) proposing a blockchain-enabled multi-settlement P2P energy trading framework that incorporates four parallel trading mechanisms to handle diverse trading preferences for different electric sources/demands along with attaining immunity against collusion between different sets of market participants (e.g., all sellers or buyers) to manipulable market price; 2) proposing a double-auction VCG mechanism, as a part of the framework, to promote participants' truthful bidding, which eliminates market power and maximizes the social welfare; and proposing remedies to the VCG-mechanism's lack of the balanced-budget property, including a novel balanced-budget VCG pricing rule that overcomes any market deficiency; 3) incorporating a novel PoC mechanism with the double-auction VCG to facilitate the consensus process of the blockchain and attain the mechanism's immunity to shill bidding via managing the digital identities of participants.; and 4) conducting various case studies to analyze the performance of the proposed P2P framework and the remedies for the VCG's lack of the balanced-budget property.

The rest of this paper is organized as follows. Section II describes the system setup. Section III elaborates the proposed multi-settlement trading framework, followed by numerical case studies in Section IV. Section V concludes the paper.

II. System Setup

Fig. 1 presents a schematic for the system setup. The distribution network is assumed to have sufficient capacity to handle different electricity transactions among the peers, as well as with the main grid. In the communication layer, peers are interconnected and can exchange data through the IoT network (e.g., a local area network (LAN) or Internet). A cloud platform is set up that is used by all peers as a client portal for managing their controllable asset and accessing the regional wholesale electricity market. In the virtual layer, a consortium blockchain is set up as a distributed ledger system.

As depicted in Fig. 2, a peer is defined as an active entity that owns and operates a group of electricity assets (e.g., DER, ES, EV, CL) and can trade its electricity generation/demand to be delivered through the common infrastructure of the distribution grid. A local communication gateway, named the "Smart

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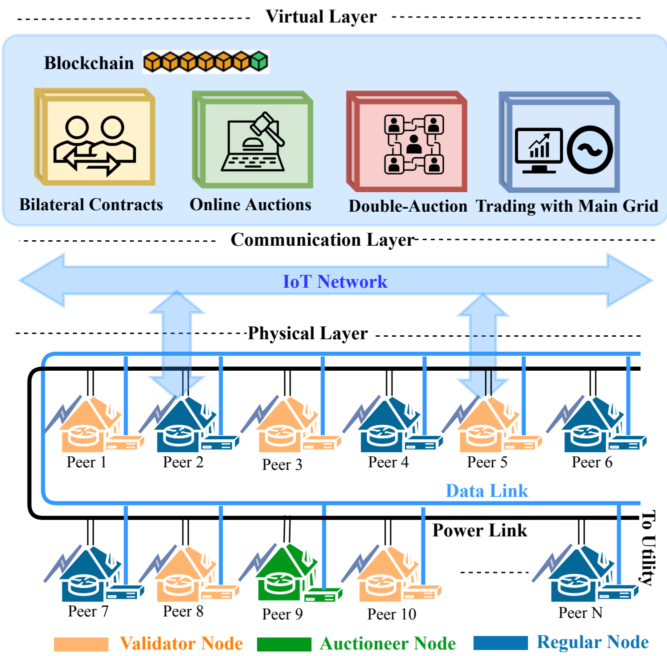

Fig. 1. A simplified schematic diagram for the system setup for a P2P framework.

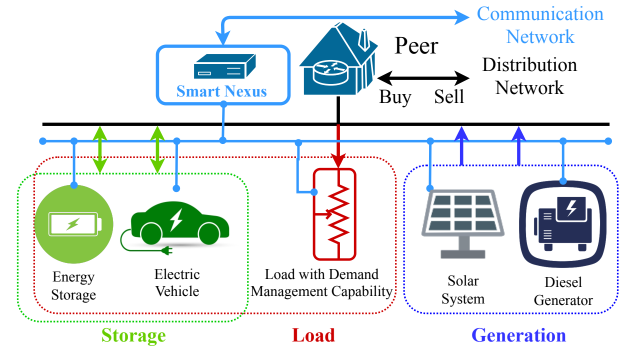

Fig. 2. A illustrative diagram for a generic peer with ESS, electric generation unit(s), passive load (PL), and/or controllable load (CL).

Nexus", is installed to integrate the peer's electricity assets. On the one hand, the Smart Nexus provides automation for energy control and management for the prosumer through local IoT protocols (e.g., WiFi, Lora, Z-Wave). On the other hand, it can communicate with its peers and the cloud platform through the available communication layer, by which blockchain-based P2P trading is performed. It is noteworthy that the form of a Smart Nexus can be flexible. It can be implemented in an edge-computing devices, server, or a personal computer with a communication interface.

A consortium blockchain infrastructure is implemented in the system to offer permissioned distributed ledger and trading management. In practical applications, the regional distribution system operator (DSO) may classify or determine the roles of registered peers based on their computational capabilities to regular or validator nodes/peers. Peers will trade their electricity generation or demand in the network though their Smart Nexus gateway. The validator network serves as miners and ledger managers in the blockchain. The validators take turns to serve as the auctioneer to clear the community auction and participate on behalf of the community in the regional wholesale market. While regular validators can participate in the trading normally, to overcome conflicts should they arise, the auctioneer node can only trade its electricity generation/demand in the double-auction mechanism (Fig. 1) if it declares/broadcasts its bids before all other participating peers.

III. The Proposed Peer-to-Peer Energy Trading Framework

The proposed framework consists of bilateral contracts, e-commerce platform, double-auction VCG mechanism, and trading with the main grid, as depicted in the virtual layer in Fig. 1. It is designed as a four-settlement system to fulfill different peers' trading preferences and asset attributes regarding electricity generation/consumption. Meanwhile, as it is impossible for any single mechanism to eliminate the vulnerability to collusion between different sets of market participants (e.g., all sellers/buyers may collude to inflate/deflate their bidding prices simultaneously) [27], the existence of multiple trading options hinders, to a high extent, the collusion between all peers of the same type (i.e., sellers or buyers). For instance, the simultaneous inflation of sellers' bids in the VCG mechanism will incentivize buyers to trade bilaterally, through online auctions, and/or with the main grid. The framework provides various opportunities for peers to correct their trading positions, which in turn offers them better handling for different uncertainties (e.g., load and renewable DER) and helps to resolve the common scalability issue of P2P market mechanisms [28] by splitting transactions among multiple mechanisms.

With a broker-free blockchain-based infrastructure, the proposed framework facilitates an open environment with minimal entry barriers, which can maximize the social welfare of its members. The time step and the clearing time of these mechanisms, except for the trading with the main grid, can be determined independently and flexibly, based on the peers' preferences and common practices. When trading agreements occur, a list of transactions will be broadcast to the validator network. By validating the rationality of the transactions, i.e., using public keys and signatures, the distributed ledger process is carried out in the validator network using consensus protocols. To expedite the computing process and save resources, the consensus process in the first, second, and fourth trading mechanisms uses the Byzantine fault tolerant (BFT) algorithm, while in the third mechanism, an improved consensus protocol, PoC, is proposed.

Fig. 3 demonstrates a flowchart for a typical trading strategy for a peer in the proposed trading framework. The four trading mechanisms of the proposed trading framework are elaborated as follows.

A. Bilateral Contracts

In a bilateral contract, two or more peers reach a settlement for an electricity transaction to be conducted at a determined

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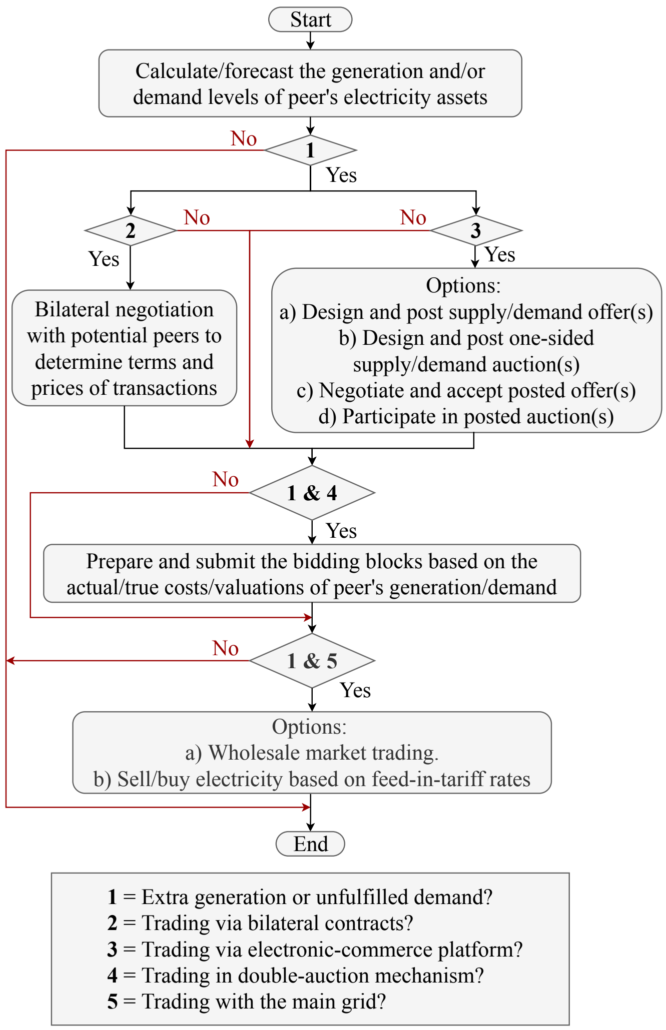

Fig. 3. Flowchart for a typical peer's trading strategy in the proposed framework.

time period with a specified price and amount of energy. Such flexible contracts could span different time scales, with different amounts of energy and for different prices. Different from the mechanism of P2P bilateral contracts in [11], [12], the contracts here are settled bilaterally through the bi-directional communication infrastructure without any central clearing mechanism. The blockchain will log the contracts into the ledger book, which is visible to all peers. An example for such useful contracts is charging an EV by clean energy from the rooftop photovoltaic (PV) system at the owner's house while parking remotely (e.g., at the office) within the system's footprint. Here, a bilateral contract may be settled to use part or all of the PV generation to charge the remotely located EV during a determined time (e.g., the sunny noon hours while being at the office).

B. Electronic-Commerce Platform (or Online Auctions)

The blockchain and P2P bi-directional information and communication infrastructure will facilitate an e-commerce cloud platform for P2P electricity negotiations and tradings. A peer can post its available energy service offer on the e-commerce platform as merchandise, while other peers negotiate the price and purchase the service. Additionally, a peer can set up a convenient type of buying/selling auction and broadcast it on the platform for interested peers to bid/participate in. The blockchain will ensure the privacy in conducted transactions, via using public and private key pairs, while facilitating smooth and secure financial transfers. Such an open market provides the flexibility to satisfy various selling/buying preferences for the heterogeneous electricity attributes (e.g., location, type of generation, reliability, location). For instance, two peers may reach a settlement to trade uncertain renewable electricity generation in a specific period of time for a specific price in \$/kWh. This can occur when the generation agent cannot accurately forecast its generation level and the demand agent can handle the electric source variability (e.g., battery charger).

C. Double-Auction Mechanism

A double-auction mechanism is proposed here to optimally allocate sell and buy bids of participating peers. An ideal double-auction mechanism should satisfy four fundamental properties:

- individual-rationality: achieve a non-negative utility for each market participant;
- economic-efficiency: maximize the total social welfare by maximizing the sum of all participants' true utilities;
- truthfulness: incentivize market participants to bid their *true* costs/valuations of auctioned items by ensuring that truthful bidding is the dominant strategy of all participants [18]; and
- balanced-budget: auctioneer should not encounter loss from running the double-auction.

All four fundamental properties, however, cannot be fulfilled in a single market mechanism, according to the Myerson –Satterthwaite theorem.

The VCG mechanism [29]-[31], which satisfies three out of the four fundamental properties, is employed for the double-auction mechanism here. The VCG mechanism is economically efficient and truthful, and is individually rational when the Clarke pivot rule is utilized. It is noteworthy that the only economically efficient mechanism that ensures truthfulness is the VCG mechanism [32]. The VCG mechanism is applicable to blockchain-based distributed implementation where the outcome is determined by the peers themselves without the need for a central auctioneer [33]. Distributed implementation respects the distributed nature of the P2P markets and blockchain, but it can also open opportunities for the participating peers to manipulate the market outcome [33]. However, since the VCG mechanism fulfills the truthfulness property, participants will not have any incentive to manipulate the market by deviating from their *true* valuation. While the balanced-budget property is the main obstacle against real implementation of the double-auction VCG mechanism, there is no ideal mechanism. A few remedies are proposed, therefore, to overcome such a drawback.

The VCG double-auction encompasses an efficient clearing mechanism and a pricing mechanism. At first, the market selling/buying (i.e., generation and demand) bids are efficiently cleared to maximize the social welfare by solving the winner determination problem (WDP). Then, instead of receiving/paying the bidding price of the winning selling/buying bids, payments are determined by the Vickrey pricing rule, where the winning selling/buying bids receive/pay higher/lower prices compared to their bidding prices, as will be discussed later in detail.

1) Winner determination problem (WDP): The WDP is an optimization problem that determines the economically efficient clearing for the market of interest. For the double-auction mechanism under study, the daily market operation is split into independent T time slots with equal duration indexed by t, where $\mathfrak{T}$ is the set of time slots in one day (i.e., $T \triangleq |\mathfrak{T}|$). Let $\mathfrak{N}_t$ denote the set of market participants at time t, which includes the set of selling/supply/generation agents at time t, $\mathfrak{N}_{G,t}$ ($N_{G,t} \triangleq |\mathfrak{N}_{G,t}|$), indexed by i, and the set of buying/load/demand agents at time t, $\mathfrak{N}_{D,t}$ ($N_{D,t} \triangleq |\mathfrak{N}_{D,t}|$), indexed by j (i.e., $\mathfrak{N}_t = \mathfrak{N}_{G,t} \cup \mathfrak{N}_{L,t}$). Each generation agent i (or demand agent j) submits its set of offers at time t, $\mathbf{O}^G_{i,t}$ (or $\mathbf{O}^D_{j,t}$) as energy blocks indexed by m (or n), where each block is defined by a maximum power for the offer block $P_{G_{i,t}}(m)$ (or $L_{D_{j,t}}(n)$) in kW and an assigned non-negative price $\lambda_{G_{i,t}}(m)$ (or $\lambda_{D_{j,t}}(n)$) for that block in $\$/kWh$. These bidding blocks represent the valuation of selling/buying agent for different levels of its generation/demand. The set of bidding profiles for market participants at time t is denoted as $\mathfrak{O}_t$, where $\mathfrak{O}_t \triangleq \left\{\mathbf{O}^G_{i,t},\ \mathbf{O}^D_{j,t}\right\}_{\forall i,\ \forall j}$.

The WDP for the time slot t could be formulated as the following linear programming problem:

$$J(\mathfrak{O}_t) = \underset{\substack{p_{G_{i,t}}(m),\ \forall m, \forall i \\ l_{D_{j,t}}(n),\ \forall n, \forall j}}{maximize} \sum_{j=1}^{N_{D,t}} \sum_{n=1}^{N_{n_j,t}} \lambda_{D_{j,t}}(n)\, l_{D_{j,t}}(n)\, dt - \sum_{i=1}^{N_{G,t}} \sum_{m=1}^{N_{m_i,t}} \lambda_{G_{i,t}}(m)\, p_{G_{i,t}}(m)\, dt \tag{1a}$$

$$\text{subject to} \quad P^G_{i,t} = \sum_{m=1}^{N_{m_i,t}} p_{G_{i,t}}(m), \forall i \tag{1b}$$

$$L^D_{j,t} = \sum_{n=1}^{N_{n_j,t}} l_{D_{j,t}}(n), \forall j \tag{1c}$$

$$\sum_{i=1}^{N_{G,t}} P^G_{i,t} = \sum_{j=1}^{N_{D,t}} L^D_{j,t} \tag{1d}$$

$$0 \le p_{G_{i,t}}(m) \le P_{G_{i,t}}(m), \forall m, \forall i \tag{1e}$$

$$0 \le l_{D_{j,t}}(n) \le L_{D_{j,t}}(n), \forall n, \forall j \tag{1f}$$

where $p_{G_{i,t}}(m)$ and $l_{D_{j,t}}(n)$ are the decision variables that indicate the cleared power level of bidding blocks m and n for generation agent i and demand agent j, respectively, at time t (i.e., the bid m of generation agent i does not belong to the optimal allocation at time t if $p^*_{G_{i,t}}(m) = 0$); $N_{G,t}$ and $N_{L,t}$ are the number of participating generation and demand agents, respectively, at time t; $N_{m_i,t}$ and $N_{n_j,t}$ are the number of bidding blocks for generation agent i and demand agent j, respectively, at time t; $P^G_{i,t}$ and $L^D_{j,t}$ are the total cleared power for generation agent i and demand agent j, respectively, at time t in kW; and $dt = \frac{24}{T}$ is the market time slot duration in hours.

Given the set of bidding profiles for market participants at time t, $\mathfrak{O}_t$, solving the WDP (1) determines the optimal allocation $\mathfrak{X}^*_t(\mathfrak{O}_t)$, where $\mathfrak{X}^*_t(\mathfrak{O}_t) \triangleq \left\{p^*_{G_{i,t}}(m), l^*_{D_{j,t}}(n)\right\}_{\forall m, \forall i, \forall n, \forall j}$, which maximizes the social welfare of the market participants. The rewards for auctioneer and miner, $\mathfrak{U}^A_t(\mathfrak{O}_t)$ and $\mathfrak{U}^M_t(\mathfrak{O}_t)$ respectively, are determined based on predefined portions, X^A and X^M respectively, of the sum of utilities of all market participants as follows:

$$\mathfrak{U}^A_t(\mathfrak{O}_t) = X^A \cdot \mathfrak{ME}_t(\mathfrak{O}_t) \tag{2}$$

$$\mathfrak{U}^M_t(\mathfrak{O}_t) = X^M \cdot \mathfrak{ME}_t(\mathfrak{O}_t) \tag{3}$$

The total market exchange at time slot t, $\mathfrak{ME}_t(\mathfrak{O}_t)$ (in \$) can be mathematically determined as:

$$\mathfrak{ME}_t(\mathfrak{O}_t) = \sum_{i=1}^{N_{G,t}} \sum_{m=1}^{N_{m_i,t}} \lambda_{G_{i,t}}(m)\, p^*_{G_{i,t}}(m)\, dt + \sum_{j=1}^{N_{D,t}} \sum_{n=1}^{N_{n_j,t}} \lambda_{D_{j,t}}(n)\, l^*_{D_{j,t}}(n)\, dt \tag{4}$$

Accordingly, the utilities of generation agent i and demand agent j corresponding to the market clearing is found by:

$$\mathfrak{U}^{G^*}_{i,t}(\mathfrak{O}_t) = \left(1 - X^A - X^M\right) \sum_{m=1}^{N_{m_i,t}} \lambda_{G_{i,t}}(m)\, p^*_{G_{i,t}}(m)\, dt \tag{5}$$

$$\mathfrak{U}^{D^*}_{j,t}(\mathfrak{O}_t) = \left(1 - X^A - X^M\right) \sum_{n=1}^{N_{n_j,t}} \lambda_{D_{j,t}}(n)\, l^*_{D_{j,t}}(n)\, dt \tag{6}$$

Clearly, $\mathfrak{U}^{G^*}_{i,t}(\mathfrak{O}_t)$ (or $\mathfrak{U}^{D^*}_{j,t}(\mathfrak{O}_t)$) equals zero if all bids of generation agent i (or demand agent j) are not selected by the optimal market clearing. The peers have the opportunity to balance their uncleared bids through trading with the main grid as discussed later in Section III-D.

2) Payment/pricing rule: The WDP (1) aims at maximizing the social welfare while each market participant aims to optimize its own/local objective by bidding in the market. Pay-as-bid, uniform-pricing, and locational-marginal-pricing rules are commonly used pricing mechanisms. However, they do not ensure the alignment of private objectives with the group objective (i.e., maximizing the social welfare). Under the pay-as-bid pricing, individual agents may overbid/inflate their bids to secure positive high profit, which leads to optimizing the inflated bids rather than the actual social welfare (i.e., inefficient market clearing) [34]. Under uniform- and locational-marginal- pricing, the market participants may be exposed to extra price volatility due to the exercise of market power by some participants [17], [35].

The VCG pricing mechanism, which belongs to the family of discriminatory pricing rules, is proposed and deployed in the double-auction mechanism to incentivize participants to

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bid truly based on their actual/true cost/valuation, which in turn leads to maximizing the actual social welfare. Under the VCG mechanism, regardless of other participants' bids, the agent cannot gain higher than is achievable by truthfully declaring the cost/valuation of its generation/demand. Meanwhile, the Clarke pivot rule is implemented to fulfill the property of individual-rationality. In double-auctions with the VCG pricing mechanism that implements the Clarke pivot rule, each selling/buying agent will receive/pay its cleared bid price plus/minus its contribution in increasing the social welfare of all the market participants. Hence, based on the VCG pricing with the Clarke pivot rule, at time t, the compensation of generation agent i and the payment of demand agent j can be formulated as:

$$\mathbb{P}_{G_{i,t}}^{VCG} = \mathfrak{U}_{i,t}^{G^*}\left(\mathfrak{D}_t\right) + \left(J\left(\mathfrak{D}_t\right) - J\left(\mathfrak{D}_t^{-i}\right)\right) \tag{7}$$

$$\mathbb{P}_{D_{j,t}}^{VCG} = \mathfrak{U}_{j,t}^{D^*}\left(\mathfrak{D}_t\right) - \left(J\left(\mathfrak{D}_t\right) - J\left(\mathfrak{D}_t^{-j}\right)\right) \tag{8}$$

where $J\left(\mathfrak{D}_t^{-i}\right)$ is the maximum social welfare (i.e., the solution of (1)) when agent i is not participating in the auction. Clearly, both generation and demand agents will receive/pay favorable payments compared to their bids.

3) Balanced-budget property and the VCG mechanism: As mentioned earlier, VCG is lacking the balanced-budget property, which intimates that it may result in insufficient revenues to the auctioneer (i.e., the total payments received by buyers may be less than the total payments to the sellers). However, the VCG mechanism is a weakly balanced-budget in every scenario as any other individual-rational, economic-efficient, and truthful mechanism can be [36].

Given the VCG double-auction mechanism, there are two main approaches to achieve the balanced-budget property: by externally subsidizing the mechanism in case of any deficiency, which ensures the maintenance of other fundamental/ideal mechanism's properties (i.e., individual-rationality, economic-efficiency, and truthfulness); and by modifying the payment rules to avoid any deficiency, which may cause a violation to at least one of the other fundamental properties. External subsidies could be available through different sources such as governmental/community initiatives for clean energy integration and/or P2P trading support, savings in transmission losses/expansions due to P2P trading implementation, and applied fees for electric transactions with the main grid to promote local energy trading.

To fulfill the mechanism's balanced-budget property, without external subsidies, three different variations are proposed as follows. The first adopts a probabilistic trade reduction mechanism [37], [38], which compromises the market's economic efficiency in favor of the balanced-budget property. The second adds negative/positive terms (e.g., constants), handled as transaction fees, to sellers'/buyers' payments in equations (7) and (8), where the sum of these accumulated fees will cover the mechanism's budget deficiency if any. To maintain the mechanism's individual-rationality and truthfulness, the added terms have to be carefully determined independent of the participants' bids. The third variation imposes limits on agents' payments as in (9) and (10), which represent the balanced-budget-compensation of generation agent i at time t, $\mathbb{P}_{G_{i,t}}^{BB}$, and the balanced-budget-payment of demand agent j at time t, $\mathbb{P}_{D_{j,t}}^{BB}$, respectively. The imposed limit is determined based on the uniform-pricing rule in (11). In (9) (or (10)), the generation agent i (or demand agent j) will be compensated (or will pay) for its cleared bids based on the minimum (or maximum) of the VCG and the uniform-pricing payments. Such variations maintain the mechanism's individual-rationality, but may violate the truthfulness, and in turn the economic efficiency, because the agent's payment may be dependent on its bid(s).

$$\begin{aligned}\mathbb{P}_{G_{i,t}}^{BB} = {} & \mathfrak{U}_{i,t}^{G^*}\left(\mathfrak{D}_t\right) \\ & + min\Bigg\{ \left(J\left(\mathfrak{D}_t\right) - J\left(\mathfrak{D}_t^{-i}\right)\right), \\ & \sum_{m=1}^{N_{m_i,t}} \left(\lambda_t^{Uniform} - \lambda_{G_{i,t}}(m)\right)\ p_{G_{i,t}}^*(m)\ dt \Bigg\}\end{aligned} \tag{9}$$

$$\begin{aligned}\mathbb{P}_{D_{j,t}}^{BB} = {} & \mathfrak{U}_{j,t}^{D^*}\left(\mathfrak{D}_t\right) \\ & - min\Bigg\{ \left(J\left(\mathfrak{D}_t\right) - J\left(\mathfrak{D}_t^{-j}\right)\right), \\ & \sum_{n=1}^{N_{n_j,t}} \left(\lambda_{D_{j,t}}(n) - \lambda_t^{Uniform}\right)\ l_{D_{j,t}}^*(n)\ dt \Bigg\}\end{aligned} \tag{10}$$

$$\lambda_t^{Uniform} = max\left\{\lambda_{G_{i,t}}(m).\left\lceil \frac{p_{G_{i,t}}^*(m)}{p_{G_{i,t}}(m)} \right\rceil \ \middle|\ m \in \mathbf{O}_{i,t}^{G},\ i \in \mathfrak{N}_{G,t}\right\} \tag{11}$$

where $\lambda_t^{Uniform}$ is the market clearing price under a uniform-pricing mechanism.

4) Immunity to shill bidding and collusion: In spite of its numerous virtues, the VCG mechanism, like other market mechanisms, is vulnerable to shill bidding (i.e., a single agent bids with multiple identities to manipulate market outcomes and in turn payments). In other words, a bidder finds participating/bidding with multiple identities more profitable than bidding its single truthful cost/valuation [27]). Yet another vulnerability is collusion (i.e., a group of bidders/participants may achieve higher collective utility by colluding and simultaneously deviating from their individual truthful costs/valuation [27]) [39]-[41]. Such vulnerabilities could be overcome by limiting the market outcome to the *core* since *core* outcomes are competitive outcomes that eliminate any incentives for collusion and shill bidding [18], [39], [42]. The *core* could be defined in the coalitional game theory as the set of auction/game outcomes that cannot be improved upon by different coalitions between agents/players. *Core* outcomes, and hence immunity to collusion and shill bidding, could be ensured by enforcing sufficient conditions on the market participants' bids as discussed in [18], [39], [43].

However, imposing conditions on the market participants' bids to achieve the immunity may contradict the mechanism's truthfulness property for some types of generators/loads (i.e., the true cost/valuation of generation/demand may not satisfy the imposed bidding conditions). It is impossible for any single mechanism to eliminate the vulnerability of collusion between different sets of market participants (e.g., all sellers/buyers may collude to inflate/deflate their bidding prices simultaneously) [27]. Hence, the immunity to collusion and shill bidding in the proposed trading framework is achieved via the existence of multiple parallel trading options and the management of peers' digital identities via blockchain implementation, respectively.

5) The proof of clearance consensus: Blockchain will provide the essential infrastructure and framework to carry the double-auction mechanism on its network. By decomposing and interacting with the VCG auction process, a PoC consensus method is proposed here to improve the efficiency in the peer network and to provide immunity to shill bidding. Fig. 4 illustrates the detailed PoC procedures based on an experimental blockchain system built in the laboratory. The process consists of 11 steps. At the beginning of every bidding cycle, one of the blockchain validators takes turns and serves as the auctioneer. The prosumers submit the bids through their client user interface (UI) to the auctioneer, who then orders the data sets and formulates the WDP. Note that, both regular and validator nodes may participate in the bidding. The WDP is broadcast to all validating peers, who compete to solve the WDP and apply the pricing rules. The winning peer who first solves the problem will broadcast its feasible solutions to the network. All other peers will validate the solution as well as the rationality of transactions. If the validation passes, the auctioneer will hash the results and broadcast the new block in the network. Thereafter, all peers will update their ledger with the new block to achieve the consensus. The cleared transactions are then formulated into smart contracts and sent back to the prosumers. Smart contracts will be executed and a transaction cycle is finalized. The auctioneer and winning validator will get the rewards as defined in (2) and (3), respectively. Note that the hardware configurations and communication protocols depicted in Fig. 4 are for example purpose only. In practice, the system can employ other protocols in accordance with actual engineering environment and hardware infrastructure.

D. Trading with the Main Grid

Some peers may not succeed in balancing their electric demand/supply locally through the aforementioned mechanisms, and/or may prefer to trade outside the local grid. In such a case, there are two options for electricity trading with the main grid. The first is to participate in the regional wholesale electricity market, if any. In traditional power system setups, the small-scale prosumers (i.e., peers) are not allowed to participate in the wholesale markets, and they can only trade with an intermediary (e.g., an aggregator). A prime benefit of the proposed system setup and trading framework is that any peer, regardless of its power capacity, can bid in the wholesale electricity market. In this case, the auctioneer is responsible for receiving the peers' bids and participating on their behalf in the wholesale markets. The second option for trading with the main grid is through a certain (i.e., predefined) but relatively unfavorable price. Each peer has the option to sell/buy electricity at a low/high price compared to the average of clearing prices in the wholesale markets (e.g., sell electricity based on the relatively low feed-in-tariff price). Such an option can be used to balance the uncleared bids in the wholesale markets as well as to avoid the volatility of market prices. In both cases, the auctioneer will pack the trading outcomes as a new block and broadcast it to be updated in the validator network.

IV. Application and Performance Evaluation

A system of 20 peers is used here to apply the proposed electricity trading framework and conduct several case studies to demonstrate and evaluate its performance. After describing the system setup, its outcomes under different trading mechanisms are analyzed and compared to study the effectiveness of the proposed trading framework with its blockchain-based, P2P double-auction VCG mechanism.

A. Case Study Setup

A distribution system that interconnects 20 peers and to the main grid (i.e., infinite bus) is considered here to facilitate the trading of peers with each other in the wholesale market, and with the main grid operator. For the sake of simplicity and without loss of generality, the grid constraints are ignored (i.e., the distribution system is represented as a single node grid). Table I outlines the set of electric loads, generators, and/or storage (i.e., PL, CL, PV, controllable generator (G), ES, EV) for different peers. All peers have PLs, but only peers #1 to #10 have CLs (i.e., demand management capability). Costs and profiles for loads, ESs, EVs, PVs, and Gs, as well as the clearing prices in the wholesale electricity market were extracted from the data sets in [44], [45]. Since the load flexibility is unknown (undetermined), the PL and CL levels for different peers with load management capability in each time period (i.e., hour) are determined from the extracted load profiles by randomly selecting the $\frac{CL}{PL}$ ratio to range between 0.2 and 0.8. Then, the peer's load is represented as a minimum and maximum load per time period, which corresponds, respectively, to the PL and the summation of the PL and the CL. Fig. 5 demonstrates the typical profiles used for the system's aggregated load, renewable generation, and the wholesale market price for one day.

Bounded by the adopted data sets, the double-auction mechanism is set to clear the received (hourly) bids on an hourly basis (i.e., 24 times a day). Each peer, through its hardware node, is assumed to attempt to balance its electric load and/or supply internally, through bilateral contracts, and/or online auctions. Then, for its unmatched load/generation (if any), it prepares and submits a bidding curve for the double-auction. For the conducted cases below, the bidding curves for electricity supply are generated based on the capacities and cost of generation extracted from [45]; the load bidding curves are determined based on the assumed load importance and/or prosumers' preferences, where the PLs (i.e., critical loads) are assigned high bidding prices, which are higher than twice the anticipated maximum daily price (e.g., \$0.2/kWh). For the purpose of the case study, the auctioneer and miner are assumed to receive equal rewards for their service with

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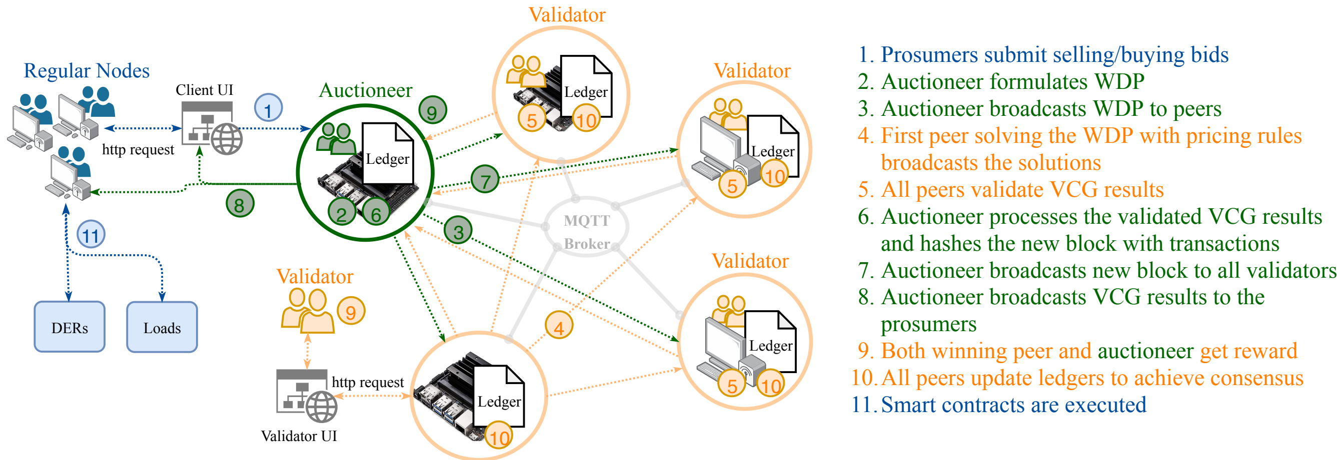

Fig. 4. The proposed PoC mechanism for the VCG double-auction mechanism.

TABLE I
THE ELECTRIC APPARATUS OF DIFFERENT PEERS IN THE SYSTEM.

Apparatus	ES	EV	PL	CL	PV	G
Peer ID	11-20	5-15	1-20	1-10	5-20	1-5

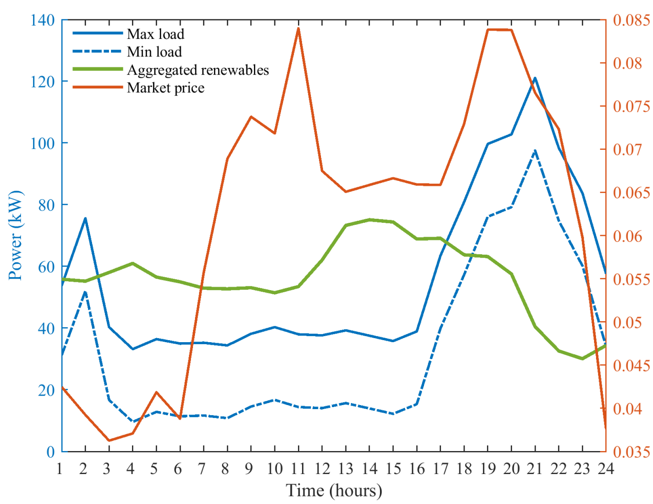

Fig. 5. The daily profiles for the system's aggregated load, renewable generation, and the wholesale market price.

$X^A = X^M = 0.01$. For the real implementation, these values could be adjusted, based on various circumstances (e.g., the market volume, number of peers, competitiveness level) to ensure the profitability and maintenance of the service. To promote local trading of electricity, a tariff/fee of $0.025/kWh was added to or subtracted from the clearing prices of the cleared peers' buying/selling bids in the wholesale markets. Meanwhile, the feed-in-tariff rates were set to be $0.015/kWh and $0.1/kWh for sell-to-grid and buy-from-grid, respectively.

B. Blockchain System Setup

An experimental blockchain system based on the configuration in Fig. 4 is set up in the laboratory. For simplicity and proof of concept purposes, the validator network is formed by five nodes running on personal computers (PCs). The hardware is interconnected via Ethernet. The ledger is stored in peers using CouchDB and the proposed PoC is implemented by Python3. The public and private key pairs for the peers are generated using Round Sheep Hash (RSH) cryptography toolbox, while the hash function SHA-256 is employed for block connection. The peers broadcast messages using the MQTT protocol by subscribing and publishing to the same MQTT broker (Eclipse Mosquitto on a Raspberry Pi Model 3+) and the same topic in a JSON format. Fig. 6 the demonstrates the UIs for both the validator and regular peers, through which the ledger and block information can be queried. Note that the system setup is for verification purposes; therefore, the prosumers' trading assets are simulated by data flows and not actual generations/loads. Nevertheless, large scale application of the proposed method will need further verification and engineering efforts. When a validator peer receives the formulated WDP from the auctioneer, the program will call the WDP solver along with the pricing rules coded in MATLAB with GUROBI optimizer. For reference purposes, each PC carries a 1.8 GHz Core i7 CPU and 16 GB RAM. The market was cleared separately for each time slot to determine the winning bids and the payments of different market participants. The execution time for each of the tried cases with the PoC was found to be less than 5 seconds.

C. Simulation Results and Analysis

To demonstrate and evaluate the performance of the proposed trading framework, especially the double-auction mechanism, the system's outcomes are compared under the following trading schemes demonstrated in Fig. 7: 1) trading with (sell to and buy from) the grid operator based on the feed-in-tariff rates; 2) trading through the wholesale market, and based on the feed-in-tariff rates for uncleared bids; 3) trading through the double-auction mechanism with uniform

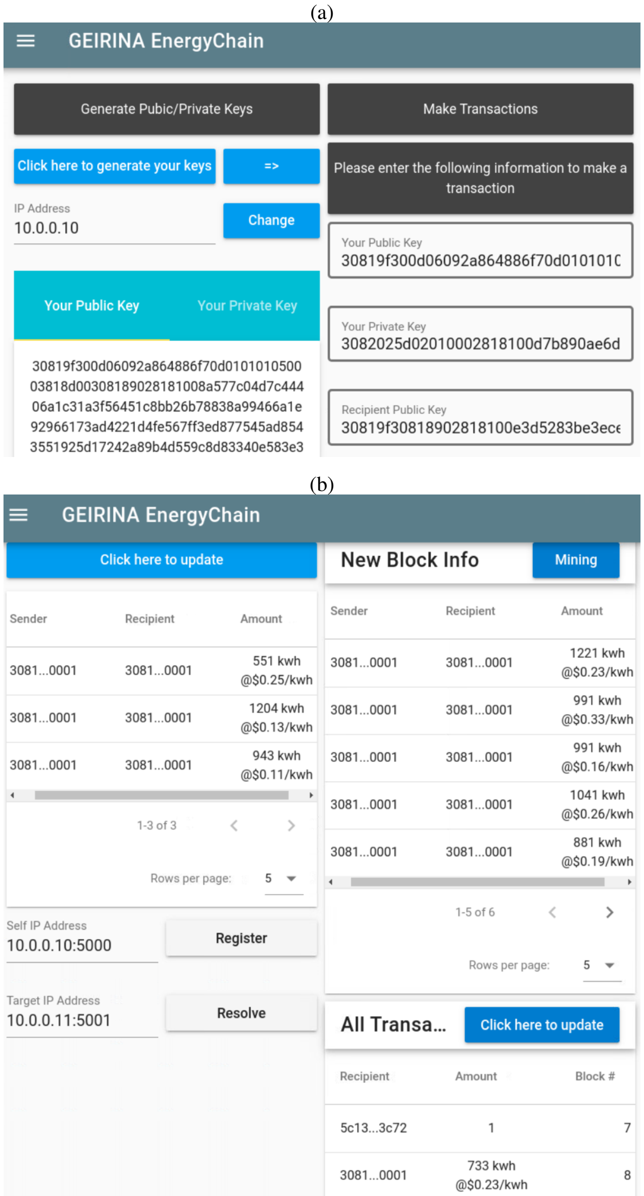

Fig. 6. Demonstration of the (a) client's and (b) validator's user interface.

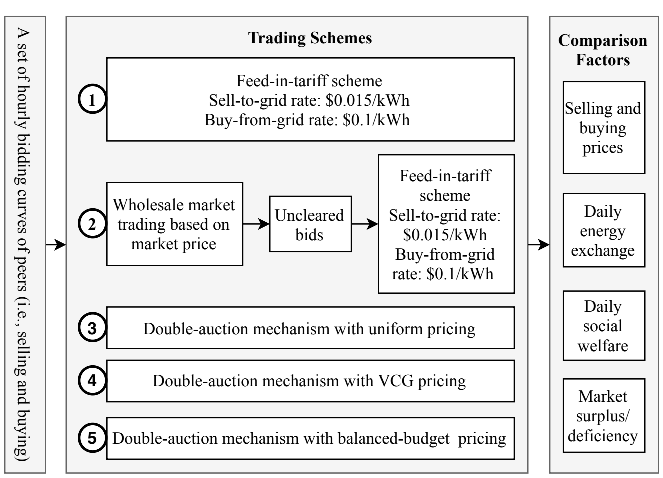

Fig. 7. A layout for the flow of the conducted simulations and analysis.

pricing; 4) trading through the double-auction mechanism with the VCG pricing rule (i.e., Eq. (7)-(8)); and 5) trading through the double-auction mechanism with the balanced-budget pricing rule (i.e., Eq. (9)-(10)). For the sake of impartial comparison, only trades that would be conducted through the double-auction mechanism, if available, are considered here. In other words, trades through bilateral contracts and online auctions are excluded (not considered) in the following comparisons. For each time slot (i.e., hour), the peers prepare and submit bidding curves, based on the real valuation/cost of their demand/generation, to trade their unfulfilled electric demand or generation surplus through the available trading options. Accordingly, the power levels and prices of cleared electric transactions can be determined, and the cleared energy exchange can be calculated.

For the adopted set of hourly bidding curves of peers, Fig. 8 shows the hourly clearing prices under the trading mechanisms of interest, namely, feed-in-tariff, wholesale market, double-auction with uniform pricing, VCG, and balanced-budget rules. Feed-in-tariff rates and wholesale market prices are uniform for all peers and independent of the submitted peers' bidding curves. In contrast, the outcomes of the double-auction mechanism depend on the peers' bidding curves, and only the uniform pricing rule applies uniform prices for all peers/participants. Under the VCG and balanced-budget pricing rules, each peer's cleared bids are assigned prices based on the peer's and/or its opponents' bids. Accordingly, Fig. 8 demonstrates the prices assigned for the cleared bids under the VCG and balanced-budget rules as scattered data that corresponds to the clearing prices assigned to different peers' bids. Most often, clearing prices in the P2P market is very competitive and more favorable than those of the wholesale market. Regardless of the clearing prices, none of the peers/participants should loose from market participation because the bids represent their actual cost/valuation, and the cleared bids are assigned favorable prices compared to their submitted prices/bids. In most instances, the P2P market with uniform pricing is better than the wholesale market from the prosumers' perspective. Moreover, some participants achieved better prices under VCG pricing than those achievable under uniform pricing. Although balanced-budget prices are not the best option for participants, they guarantee no hourly loss (i.e., deficiency) from running the double-auction.

The differences in clearing prices for different trading schemes (Fig. 8) cause differences in the total conducted energy exchange (i.e., total cleared energy) under these schemes, except for the double-auction mechanism with different pricing rules (i.e., schemes #3-5 in Fig. 7) where the WDP determines the cleared energy based on the submitted bids but not on the implemented pricing rule. For the given set of bidding curves, Fig. 9 illustrates the hourly total energy exchange for one day under feed-in-tariff, wholesale market and feed-in-tariff, and the double-auction P2P market, and the total requested energy exchange (i.e., aggregated bids). The energy exchange corresponds to the aggregated bids, which assumes that all the submitted bids are cleared. Distinctly, the P2P market based on the double-auction mechanism achieved higher energy exchange compared to the feed-in-tariff without and

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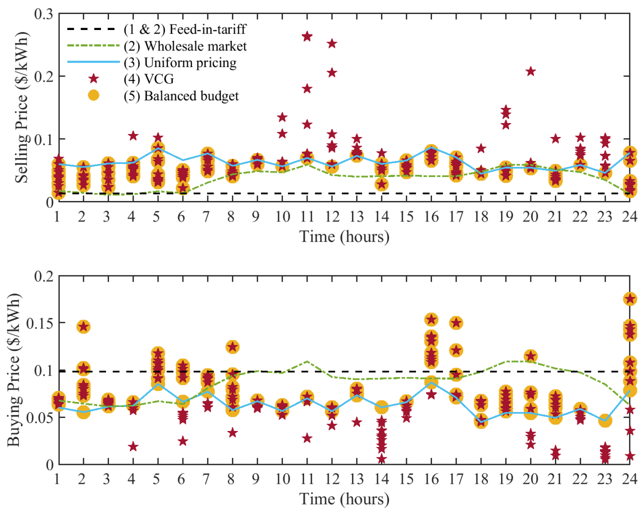

Fig. 8. The hourly selling and buying prices of the trading schemes under comparison (Fig.7) for one day. The scattered data corresponds to the clearing prices for different participants under VCG and balanced-budget rules.

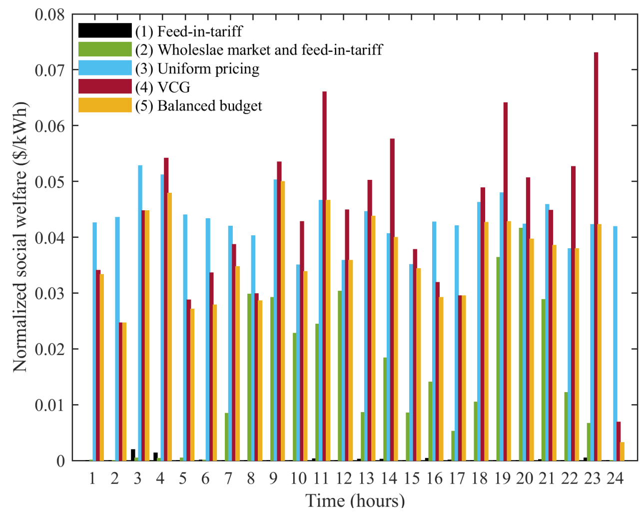

Fig. 10. The hourly normalized social welfare of the trading schemes under comparison (Fig.7) for one day.

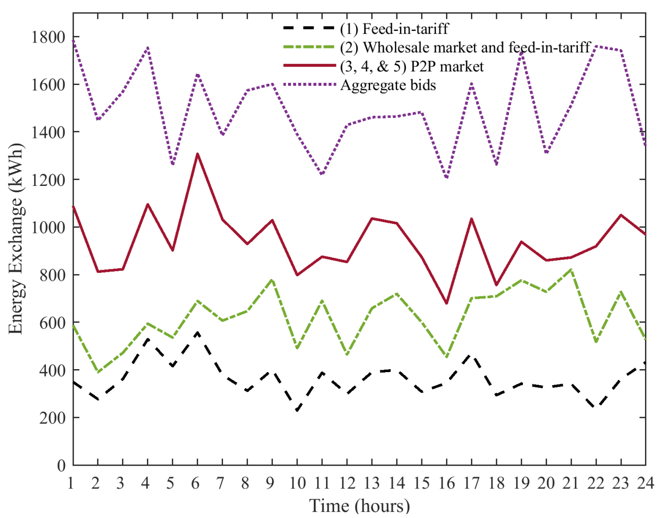

Fig. 9. The hourly cleared energy exchange based on the trading schemes under comparison (Fig.7) for one day, along with the total requested energy exchange (i.e., aggregate bids).

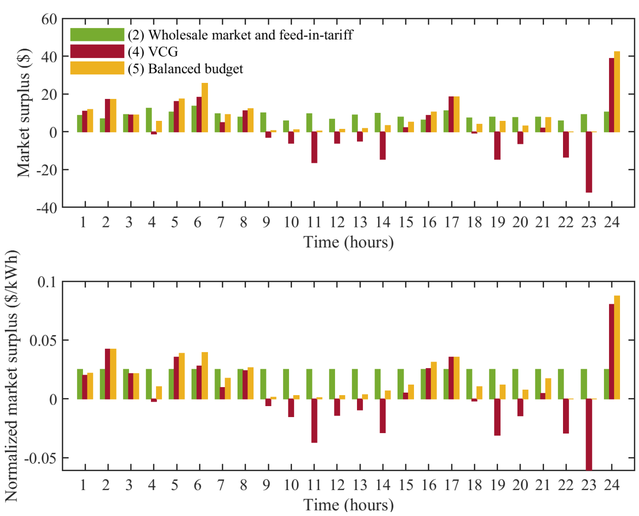

Fig. 11. The hourly market surplus/deficiency (in $) and normalized market surplus/deficiency (in $/kWh) for trading schemes #2, #4, and #5 in Fig. 7 for one day.

with wholesale market, because of its competitive selling and buying prices. Meanwhile, the P2P market achieved higher social welfare and normalized social welfare (in $/kWh) (Fig. 10) because of the higher cleared energy exchange and better clearing prices. Obviously, this will be reflected in the peers' consolidated electric bills or incomes from market trading. For the P2P market, the social welfare as well as the normalized social welfare under the VCG rule are always better than or equal to those under the balanced-budget rule because the VCG price is always better than or equal to the balanced-budget price from the peers' perspective. The hourly rewards for auctioneer and miner, with $X^A = X^M = 0.01$, over the executed 24 hours were found to range from $0.6 to $1.2 with an average of $0.8.

As discussed earlier in Section III-C, the only issue of implementing a double-auction market with a VCG pricing rule is the possibility of market deficiency occurrence. Under the uniform pricing rule, a market surplus or deficiency cannot occur because the sum of payments by buyers equals to the sum of payments to sellers. The balanced-budget rule may only achieve a market surplus but not a deficiency. For trading in the wholesale market, the operator will generate a market surplus through the collected transaction fees (i.e., $0.025/kWh) for cleared energy. Fig. 11 and Table II demonstrate the market surplus/deficiency (in $) and normalized market surplus/deficiency (in $/kWh) under the trading schemes #2 (i.e., wholesale market and feed-in-tariff), #4 (i.e., double-auction with VCG pricing rule), and #5 (i.e., double-auction with balanced-budget pricing rule) in Fig. 7 for one day. From Figs. 10 and 11, it could be noted that the social welfare and the normalized social welfare under uniform pricing rule is always the best/highest unless a market deficiency occurred

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TABLE II
PARAMETERS OF MARKETS' SURPLUS/DEFICIENCIES DEMONSTRATED IN FIG. 11. (1) MARKET SURPLUS/DEFICIENCY ($), (2) NORMALIZED MARKET SURPLUS/DEFICIENCY ($/KWH)

	Minimum		Maximum		Average		Daily Total	
	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)
Wholesale	5.7	0.025	13.5	0.025	8.8	0.025	210.6	0.6
VCG	-31.9	-0.06	38.8	0.08	2.2	0.005	52.7	0.11
BB	0	0	42.3	0.087	8.8	0.019	212.8	0.45

under VCG pricing (i.e., hours #4, 9-14, 18-20, and 22-23). In such a case, the social welfare under VCG pricing will be the highest, while the social welfare under uniform pricing will be higher or equal to that of the balanced-budget pricing rule. Although the VCG pricing rule can lead to market deficiency at some individual hours, Table II shows that it achieves a market surplus (i.e., $52.7 or $0.11/kWh) for the whole simulated day. The same conclusion was found to be valid for all other simulated days. Hence, for a newly introduced P2P market, the VCG pricing rule could be applied to utilize all its advantages detailed in Section III-C. In the course of time, if the market deficiency is found to be an issue and cannot be overcome by accumulating the market surpluses/deficiencies over time, the balanced-budget pricing rule can be implemented instead. Moreover, the switching between the VCG pricing and balanced-budget pricing rules over time, without participants' prior knowledge about the switching schedule, can be another solution to partially benefit from the VCG pricing properties while fulfilling the balanced-budget property.

V. CONCLUSIONS

In this paper, a new P2P energy trading framework enabled by blockchain is proposed. It consolidates four trading mechanisms to satisfy various trading preferences for participants as well as different attributes of electricity generation and/or consumption. A double-auction VCG mechanism is incorporated to eliminate any potential for market power exercise and maximize the actual social welfare by inducing truthful bidding as a dominant strategy for participants. As the VCG mechanism lacks for the balanced-budget property, different remedies were proposed to overcome such a drawback including a novel balanced-budget VCG pricing rule. The existence of multiple trading options/mechanisms helps with the framework's immunity against collusion; and the incorporation of blockchain helps with the VCG's immunity against shill bidding. Different case studies are conducted based on a system of 20 peers/prosumers to demonstrate and evaluate the performance of the proposed trading framework. Results show the effectiveness of the proposed remedies to overcome any possible market deficiency and demonstrate the framework's potential to boost the social welfare of its participants.

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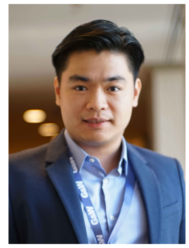

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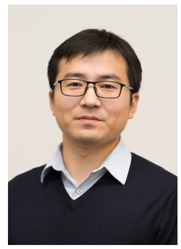

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