2021-05-19

Optimizing Blockchain Based Smart Grid Auctions: A Green Revolution

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***Abstract*—Integrating blockchain with energy trading is a new paradigm for researchers working in the field of smart grid. In energy trading, auction theory plays an important role to ensure truthfulness, rationality, and to balance utility of participants. However, traditional energy auctions cannot directly be integrated in blockchain based auctions due to the decentralized nature. Therefore, researches are being carried out to propose more efficient decentralized auctions for energy trading. Despite of all these advances, a greater standpoint that is not well-highlighted or discussed in majority of proposed mechanisms is the integration of green aspect in these auctions. Since, blockchain is a novel paradigm to ensure trust but it also comes up with a curse of high computation and communication complexity which eventually causes resource scarcity. Therefore, there is a need to develop and encourage development of more green auctions to carry out decentralised energy trading. In this paper, we first provide a thorough motivation of decentralized auctions over traditional auctions. Afterwards, we provide in-depth design requirements that can be taken into consideration while developing such auctions. After that, we analyse technical works that have developed blockchain based energy auctions from green perspective. Finally, we summarize the article by providing challenges and possible future research directions of blockchain based energy auction from green viewpoint.**

***Index Terms*—Smart Grid, Blockchain, Energy Auction, Green Energy, Green Auctions, Green Blockchain**

I. Introduction

Till now, plenty of blockchain based auction approaches have been developed by researchers and certain traditional auctions such as double price, Vickrey, and first price auctions, etc, have been integrated into blockchain based energy trading, but this domain still faces certain issues and one of the major issue is the scarcity of resources [1]. Usually, smart meters acting as blockchain nodes are computationally inefficient to carry out complex consensus, or sometimes, the storage capability of certain nodes is not effective enough to store the continuously generated data on ledger. Therefore, there arises a need to develop such type of computationally efficient mechanisms and architectures that can be integrated with decentralized grid scenarios. Certain technical works have been carried out by researchers to address this problem, but it needs to be dealt on a larger scale and a foundation of green auctions for blockchain based energy trading needs to be implied to integrate blockchain technology to maximum possible level.

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In this paper, we present a comprehensive overview of ways that can be adopted to optimize blockchain based energy auctions in order to overcome resource scarcity issues. Firstly, we discuss basic fundamental technologies along with motivation of decentralized blockchain based energy auctions. Then we provide a detailed discussion about design requirements that what parameters can be incorporated in decentralized auctions to enhance the green aspect in them. Afterwards, we carry out a thorough investigation over all the decentralized auction approaches proposed till now.. We mainly by discuss the type of green parameters these works have used and what others aspects can be used in future to enhance the proposed mechanisms. Finally, we conclude the article by providing an in-depth insights about possible challenges and future research directions that can be critical for researchers working in the field of decentralized energy trading.

A. Scope and Contributions of Our Work

Our article provides a thorough investigation over the topic of green auction design for blockchain based smart grid systems. Certain key contributions of our work are as follows:

- We discuss fundamental technologies and objectives that can play the part in designing of green decentralized energy auctions.
- We highlight designs requirements that needs to be taken care of while developing infrastructure and algorithms for green auctions in blockchain based energy trading domain.
- We survey the existing technical works and provide a viewpoint that what aspects can be improved in these works to make them more oriented towards green perspective.
- We summarize certain challenges, research directions, and open issues for researchers working in the field of green auction design for blockchain based smart grid.

B. Comparison with Related Survey Works

Till now, several surveys have been published that have highlighted various aspects of blockchain and smart grid [2]–[6]. For instance, authors in [2] provided a detailed overview about applications and potential trends regarding integration of blockchain in smart cities. Authors surveyed the effects of blockchain in smart grid, smart transportation, supply chain, and other similar domains. Similarly, another work that thoroughly surveyed the integration of blockchain in future smart grid architectures have been carried out by authors in [3]. Another work that highlights the privacy issues in blockchain

TABLE I
COMPARISON SUMMARY OF PREVIOUSLY PUBLISHED SURVEY ARTICLES WITH FROM PERSPECTIVE OF CONTRIBUTION AND SCOPE. ✔ MEANS THE TOPIC IS COVERED, ✗ SHOWS THE DOMAIN IS NOT COVERED, AND ✻ MEANS THAT DOMAIN IS PARTIALLY COVERED.ACRONYMS: SMART GRID AUCTIONS (SGA), GREEN SMART GRID (GSG), GREEN ENERGY (GE), BLOCKCHAIN INCENTIVES (BI), AND TYPES OF BLOCKCHAIN AUCTIONS (TOBA).

Major Domain	Ref.	Year	Contribution Summary	Scope				
				SGA	GSG	GE	BI	ToBA
Blockchain in Smart Cities	[2]	2019	A comprehensive review of application and potential of blockchain in smart cities.	✻	✗	✻	✔	✻
Blockchain in Smart Grid	[3]	2020	A brief literature review about integration of blockchain in future smart grid.	✻	✔	✔	✻	✗
Differential Privacy in Blockchain	[4]	2020	An in-depth survey of integration of differential privacy in blockchain layers and applications.	✻	✗	✗	✔	✗
Smart Contract for Blockchain	[5]	2020	A systematic review of usage of smart contracts in blockchain technology.	✗	✗	✗	✻	✻
P2P Energy Trading	[6]	2020	An overview of P2P energy trading from perspective of physical & virtual layer.	✔	✗	✻	✻	✔
Green Auction Design for Blockchain based Smart Grid	This Work	2020	A comprehensive analysis about design requirements and methodologies for overcoming resource scarcity in order to develop green auctions for blockchain based smart grid energy trading.	✔	✔	✔	✔	✔

and their countermeasures using differential privacy have been presented in [4]. Similarly, the possible use cases and the significance of smart contracts in blockchain scenario has been extensively reviewed by authors in [5]. One more work that provide in-depth insights about peer-to-peer (P2P) energy trading in physical and virtual layer have been presented in [6]. Complementary to all these surveys, our work highlight the aspect of green auction design in blockchain based energy trading. We provide extensive design requirements along with a thorough analysis about all technical works that proposed decentralized energy auctions. To the best of our knowledge, this is the first article that highlights the aspect of green auction in blockchain based energy trading in detail from a design viewpoint.

C. Paper Organization

The remainder of the article is organized as follows: Section 2 provides motivation and fundamentals of green auctions in blockchain based smart grid, Section 3 highlights design requirements that should be incorporated to design green auctions. Section 4 surveys existing technical works along with providing the insights that how these works can be improved to overcome resource scarcity in future. Section 5 highlights significant challenges and future research directions for researchers interested to explore this field further. Finally, Section 6 concludes the article.

II. FUNDAMENTALS OF GREEN AUCTIONS FOR BLOCKCHAIN BASED ENERGY TRADING

Game-theory and blockchain are playing a significant role in development of modern energy auctions. In this section, we first provide the motivation of such auctions and then we discuss types and objectives of blockchain based energy trading.

A. Motivation of Blockchain based Energy Auctions

Smart grid energy trading is advancing rapidly and auction mechanisms are playing a vital role in this development. Certain parties such as smart homes, prosumers, energy buyers, grid controller, etc., are involved in these auctions, therefore, it is important to incentivize each participant in the best manner in order to maintain their motivation level [7]. These energy auction mechanisms ensure truthfulness, but due to central entity, they lacks a perception of trust among participants. In order to overcome this issue of trust, decentralized blockchain technology came up as a rescuer. In blockchain based auction mechanisms, all blockchain nodes have a copy of distributed ledger, so no specific node have control over the whole data. This decentralized storage provides transparency and ensures that none of auction record can be altered once it gets recorded because everyone have a copy. Moreover, this record is maintained and updated via strong consensus mechanism that is is carried out among mining nodes, which enhances the trust a bit further. Due to these aspects, plenty of researchers have directed their research towards development of blockchain based energy auction and it is being considered as a future of energy trading in modern smart grid [8].

B. Types of Auctions in Green Smart Grid

Plenty of researches have been carried out in the field of decentralized blockchain, however, considering a broader perspective, the two most used auctions types on blockchain based energy auctions are double auctions and Vickrey auctions. Apart from these two major auctions, certain other auction strategies that work over the principal of first price auction have also been formulated by researchers in the field of blockchain based energy trading. We categorize these auctions under the category named as "Conventional First Price Auction". In this section, we define the basics and pricing rule of these auction mechanisms from perspective of decentralized energy trading. However, before moving towards different types of auctions it is important to know certain base terminologies that are commonly used in auctions such as bidder, bid, ask, pricing rule, etc, which are discussed in Table II.

TABLE II Basic Terminologies Used in Energy Auctions along with their Definitions

Terminology	Definition
Allocation Rule	A pre-defined rule which is used to find the winner of an auction process.
Bidder	A bidder is the participant who shows interest in purchasing a specific energy slot by putting forward some valuation for the slot.
Energy Slot	A specific time slot during which a specified amount of energy is available at sellers.
Hammer Price	Final price of a commodity selected by auctioneer or algorithm.
Pricing Rule	A pre-defined rule which is used to determine the final price of auction process.
Payment Method	A pre-decided method to pay for purchased energy (it could be on-chain and off-chain).
Seller	Seller is the entity who owns the energy and is willing to sell the stored energy in a specific time slot.
Valuation	A monetary value for any specific time slot which buyers are willing to pay (this could be public or private).

1) Double Auction: The functioning of double auction mechanism lies in the phenomenon that both buyers and sellers are bidding for the nominated energy slot. Energy buyers tends to get the lowest price, while on the other hand prosumers or energy sellers try to sell the energy in the maximum possible price. Furthermore, buyers compete with other buyers to purchase energy for a determined slot and sellers compete with other sellers to sell energy in order to enhance their utility. In this way, an energy demand-supply curve is formed which is used to predict the outcome and market clearing price (MCP) of energy auction. Readers interested to find more detailed discussion about demand-supply curve in double auction can study the work carried out by Zhang *et al.* in [9]. In traditional energy auction, the final payment/MCP is calculated by centralized auctioneer via above defined matching process. However, in decentralized blockchain based energy auctions, the complete process is carried out in a decentralized manner, so every buyer and seller can view and verify the demand-supply curve to ensure authenticity. After finalizing MCP, the winning buyers pay the amount they bid ($P_j(S) = b_j$) for the specified slot, which is also known as buyers payment.

2) Vickrey Auctions: Vickrey auctions lies in sealed-bid auction types in which buyers do not share their valuation/bids publicly and instead submit their valuations to some trusted auctioneer. Generally, Vickrey auctions are divided into two further types named as *k-th-price* auction and Vickrey-Clarke-Groves (VCG) auction.

a) K-th-price Auction: In this type of auction, the winner is the one who pays the highest bid. However, the final price p_j depends upon the value of k^{th} bid, and this value of k determined before starting of auction. For instance, in Vickrey second price auction (k =2), the highest bidder wins the energy slot, however, it will pay the second highest bid.

b) VCG Auction: VCG auction is a generalized form of Vickrey auction, in this auction, buyer pays the amount of harm it causes to other buyers due to its presence.E.g., in a decentralized VCG auction, N energy buyers submit their valuations $V = \{b_1, b_2, ...b_N\}$ for a specific energy slot (s) to the network for winner determination and price section. After completion of the specified time along with reception of all bids, the VCG mechanism is used to determine the final price $P = \{P_1, P_2, ...P_N\}$ and allocation vector for the bidders. The price of each energy buyer is determined on the basis of harm its valuation causes to other buyers, which is determined by using following formula:

$$P_i(B) = \underbrace{\max_{b \in V} \sum_{k \neq j} B_k(b)}_{\substack{(A) \\ without\ winner\ k}} - \underbrace{\sum_{k \neq j} B_k(b^*)}_{\substack{(B) \\ with\ winner\ k}} \quad (1)$$

In the above equation, b^* is the output of winner chosen with respect to highest bid, k works as an iterative parameter which iterates through all submitted bids except for the winning bid from bidder j. In equation, part (A) is the accumulated sum of all the bids without participation of winner j, while part (B) is the accumulation of bids including the winning bidders bid.

3) Conventional First Price Auctions: Apart from two major auction types, other auctions in smart grid energy trading can be categorised under the category of conventional/traditional first price auctions. In conventional first price auctions, highest bidder wins and pays the bidding price for the energy slot. However, the steps to carry out auction can vary. For instance, in sealed bid first price auction, all bids are hidden. Contrarily, in open-cry first price auction all bids are public at the time of auction. A detailed discussion about integration of first price auctions in green blockchain based energy trading has been provided in Section. IV-C.

C. Objectives of Energy Auctions

Auction theory in energy trading is used to get maximum benefits from auction processes which in turn benefits all participants of auction including buyers, prosumers, main grid, etc. Every auction mechanism have some objectives, for instance, some provide maximum social welfare, while other incentivize sellers, etc. However, three objectives can be defined as universal auction objectives which usually all auction mechanisms tries to achieve are as follows:

1) Social Welfare Maximization: In a decentralized energy auction, social welfare can be termed as sum of individual utilities of all participants, and individual utility is the amount of benefit every participant gets while participating in the auction process. For instance, a buyer valued an energy slot for \$50 and the final price he paid after auction calculation is \$40, then the utility of buyer ($U_b = \$50 - \$40$) will be \$10. Similarly, the difference between final price and ask of an energy seller is termed as utility of prosumer or energy seller. A utility value greater than zero shows that the profit is gained by the particular participant. In this way, the summation of utilities of all participants is said to be social welfare of the network [10]. Therefore, energy auction mechanism are designed in such a manner that they maximize the social welfare of the whole network.

2) Individual Rationality: An energy auction process will be individually rational when each participating buyer and seller have non-negative utility at the end of auction. It is done by developing energy auctions in such a manner that buyers and sellers are charged and paid exactly according to their bids and asks respectively [11]. Therefore, it is important to keep the aspect of individual rationality as a significant parameter while development of energy auctions.

3) Equilibrium: Equilibrium in auctions is a concept of game theory which is used to analyse the behaviour of participating buyers and sellers, which is further used for various statistical processes such as market analyzation, etc [12]. Multiple equilibrium types have been developed by researchers to maximize benefit of auction such as Bayesian equilibrium, mixed-strategy equilibrium, correlated equilibrium, etc. However, the most commonly used equilibrium solution in energy based auctions in Nash equilibrium, which makes sure that none of the participant can get more benefit by changing their playing strategy unilaterally provided that the strategies of other participants remains constant. While developing an energy auction, researchers aim to achieve the most desired equilibrium type by developing incentive strategies accordingly.

Apart from these three major objectives, certain other objectives that come up from perspective of blockchain based energy trading can be termed as follows:

4) Smart Contract: Smart contract can be termed as a fixed set of code which executes itself when specified conditions met [5]. In case of blockchain based energy auctions, smart contract is usually used to perform allocation and pricing in an efficient manner. Smart contract is stored on blockchain and they can be executed at the time of need. Smart contract provides the flexibility to its users that they can choose between multiple operation at the time of auction. For instance, various of energy efficient auctions can be adopted on a single blockchain network by just varying the smart contract. Contrarily, in a hardcoded blockchain code, the users do not have this feature. Therefore, majority of modern blockchain based energy auctions are integrating smart contract in their work.

5) Transaction Cost Enhancement: Another objective that blockchain based energy auctions are trying to meet is to reduce to the size of auction transactions to as much degree as possible. This is being done in order to overcome the resource scarcity issue of blockchain. Since blockchain is a decentralized distributed ledger and every node has a copy of the ledger, but all blockchain nodes do not have that much of liberty to store millions of records [13]. Therefore, in order to meet the need of ever-growing auction data, research is being carried out to reduce the transaction size in order to save transaction storage cost. This aspect of transaction cost enhancement is further elaborated from perspective of energy efficient storage in Section. III-D.

6) Enhancing Energy Demand and Consumption: Efficient energy utilization plays an important role during development of blockchain based energy auctions because it determines the effectiveness of any decentralized auction mechanism [14]. Within the domain of efficient energy utilization, researchers especially focus over two aspects. One from perspective of meeting energy demand of an area/suburb, and second to maintain a healthy ratio between consumption of energy with respect to its generation from renewable resources. This objective of efficient energy usage is further divided to develop various design requirements in energy auctions, which is discussed in Section III.

III. Design Requirements for Green Auctions in Blockchain based Smart Grid Energy Trading

In this section, we highlight certain design requirements which can be considered while developing auction mechanisms in order to enhance them to be greener from communication, computation, and energy perspective.

A. Energy Efficient Blockchain Communication

Since blockchain works over the phenomenon of decentralized distributed ledger, therefore, every node of blockchain will be connected with each other via some wireless technology. So, every new update in the network is broadcast to all other participating nodes. This redundant retransmissions and broadcast causes certain communication related issues such as high energy usage, channel attenuation, noise, etc [15]. Certain communication strategies and mechanisms have been used by researchers to overcome communication cost, for instance, usage of bloom filters, push and announce requests, flooding, gossiping, etc [16]. However, research has not been carried out from perspective of sharing auction data in the most proficient manner.

Discussion: Overcoming communication cost is one of the most significant challenge in blockchain systems because of redundant transmissions in case of every new update. Plenty of aspects in blockchain based auctions can be enhanced to perform energy efficient communication. Firstly, reduction of string length in auction message broadcast can play a significant role. For instance, finding the best combination of data that conveys all parametric requirements of auction can be found. Secondly, usage of green communication mechanisms which either use minimum energy or use the available spectrum in an efficient manner needs to be taken care of. For example, blockchain nodes can be converted to cognitive radio nodes in order to utilize spectrum efficiently.

B. Energy Efficient Consensus for Blockchain

Consensus mechanism is considered to be the heart of any blockchain network because carrying out decentralized consensus was the starting point which distinguished blockchain from other distributed computing systems. However, the first blockchain consensus mechanism (proof of work (PoW)) require miners to solve computationally complex puzzle to mine the block, which require very high computational power. Afterwards, certain other mechanisms such as proof of stake (PoS), proof of burn (PoB), proof of Elapsed Time (PoET), etc, have been developed for different applications.

Discussion: Consensus mechanisms play an integral part in sustainability of blockchain network, but development of a consensus mechanism that incorporate various parametric aspects of blockchain based smart grid auctions needs to be considered. Authors in [17] developed an energy oriented consensus for P2P energy trading which can be considered as a first step toward green consensus design purely for energy trading. However, there is still a large room which can be explored, and researches can be carried out in plenty of directions of green consensus design. For instance, one direction could be to develop more energy efficient consensus that is purely oriented for blockchain based auctions. Another approach could be to develop such consensus mechanisms which work over energy generated from renewable energy resources (RERs). Overall, we believe that green consensus design can serve as a prospective direction to make blockchain based auction greener.

C. Energy Efficient Auction Design

As auction is the core component of blockchain based smart grid auctions, so if one wants to enhance the performance of such mechanism from green perspective then the first thing to consider is to enhance the performance of auction mechanism in a way that it lies under the umbrella of energy efficient auction.

Discussion: As discussed in earlier sections that auction theory is a pretty old domain of statistics, however, researches are still being carried out to develop energy efficient auctions. For instance, single unit first price auctions carried out for 500 energy slots and 500 bidders will take far pretty less computational resources as compared to VCG auction carried for similar number of bidders and sellers. It is because in case of VCG auction one has to compute loss caused by each buyer to all other buyers. However, the game-theoretic aspects such as truthfulness, rationality, etc, of VCG auction are more dominant over first price auction. Therefore, while development of energy auctions for blockchain based smart grid, researches need to consider the aspect of energy and computational consumption along with providing rationality, truthfulness, and equilibrium.

D. Energy Efficient Auction Data-Storage (On-Chain & Off-Chain)

Blockchain data storage has been in discussion since the advent of blockchain because data of blockchain is increasing with the addition of every new blocks in the ledger. This is required to ensure trust, however, certain nodes are not capable of storing massive amount of data. Therefore, researches are focusing over both type of storages, on-chain and off-chain [18].

Discussion: From perspective of blockchain based smart grid auction, both of the data storing approaches can be considered as both have their pros and cons. For instance, if one store complete auction and trading data on-chain, then the nodes (especially smart meters) needs to have high storage capability to store it. Contrary to this, if the complete data is stored off-chain then one gets deprived of various useful advantages of blockchain such as trust enhancement, etc. Therefore, one need to consider both pros and cons of each strategy while development of auction. There are plenty of prospective directions for this requirement, for instance, one can store only transaction history on smart meter nodes and store the rest of data in external database. Another direction is to use external storage for blockchain nodes. Similarly, another direction could be to optimize auction data in such a way that it utilize minimum storage, for instance, removing excessive data which might not be required for any future usage. Considering these aspects, it can be said that storage mechanisms needs to be modified from perspective of blockchain based energy auctions.

E. Green Auction Data Analytics for Future Operations

Data analytics is not directly linked with auction design, but it definitely has links with the stored data. As discussed in the above subsection that green methods needs to be adopted for auction data storage, similarly, the integration of green data analytic strategies while analysing auction data can play a major role in development of a complete green and cost friendly system [19].

Discussion: Data analytic plays a critical role in controlling overall cost of network because of the reason that majority of auction data is collected for the purpose future forecasting. E.g., how much energy is generated from a specific resource, or how much energy is purchased in a specific suburb, etc. Therefore, development of such data analytic mechanisms which are energy and resource efficient needs to be considered. One direction could be development of innovative architecture that utilizes energy resources in the most efficient manner, another direction could be to design such data processing frameworks which consumes minimum resources to analyse maximum data, another direction could be integration of RERs based energy in analytics, etc. So, strategies needs to be developed and action needs to be take in direction of green data analytics for blockchain based smart grid auctions.

F. Energy Harvesting Nodes for Blockchain Auction Network

Harvesting energy from various environmental factors to power electronic devices is one of the most promising strategy to eliminate battery dependency. In order to so, more than 5000 different research works have been carried out till now [20]. However, harvesting energy for blockchain nodes is still a new domain and very minimal work has been carried out in this direction. Although, it is a new domain, but this concept of energy harvesting blockchain nodes have strong roots and can help in a much deeper manner towards development of green blockchain based smart grid auctions.

Discussion: In order to incorporate the concept of energy harvesting in blockchain based energy auctions, firstly, it is important to analyse and identify potential deployment places. For instance, one potential framework could be to integrate the concept of energy harvesting with blockchain based smart metering nodes, so that these nodes could power themselves at the time of auction and consensus process. Another possible direction could be to integrate energy harvesting only with controlling/mining nodes which are responsible to carry out extensive computational tasks. The second important aspect while integrating energy harvesting phenomenon in blockchain based auction is to figure out optimal material and manufacturing details for harvesting devices. For example, it is important to evaluate that which specific type of energy harvester suits the best? and what is the best framework to design them up? Similarly, the aspect of cost can also not be ignored while designing energy harvesting devices for blockchain based auction systems. However, it is worthwhile to mention that the aspect of integration of energy harvesting with blockchain based energy auctions could play a significant role if its carried out in a proper direction. Because it can save a massive amount of energy which is consumed during mining, consensus, and other blockchain processed. Therefore, integration of energy harvesting in blockchain based smart grid nodes is a much needed approach in future, as it will help to improve self-sustainability of blockchain network.

G. Green Energy Scheduling for DSM Enhanced Auctions

Demand side management (DSM), which is used to control and balance demand and supply of energy is an integral part of modern day smart grid system. Previously, only shaping the energy usage was considered the only option to manage peak-to-average ratio (PAR), however, nowadays it has been proved by research that it is not the only solution and plenty of other mechanisms can also play their role in DSM [21]. Researches have been carried out and efficient energy storage, scheduling, and trading is considered to be one of the most promising ways to reduce PAR in areas where there is high ratio of prosumers.

Discussion: Scheduling green renewable resources-based energy is also in discussion due to increased interest in efficient DSM. Energy is being scheduled by user in order to sell them at the time of high need. This trading is being carried out via blockchain based auction systems, which are responsible to provide optimal revenue in return of energy. Scheduled energy is a great way to enhance green aspect and to reduce the probability of blackouts in the area, because the green energy can be stored and used at the time of need. In order to understand it further, lets take the example of a user X which has a specified amount of energy stored in the batteries that he wants to sell. So, instead of selling the energy straight away it can auction for a specified time slot when energy demand is considerably high. Similarly, another prosumer can purchase and store energy at the time of low prices and can sell at the time of need and all this can be done via P2P energy trading carried out via blockchain. An interesting work in this direction has been carried out by authors in [22], who developed a grid influences strategy for this process. However, this aspect of green energy scheduling for blockchain based energy trading needs more exploration in future.

IV. Blockchain based Auction Approaches for Green Smart Grid

Various technical works integrating different types of auctions strategies in blockchain based energy trading have been carried out by researchers till now. On a broader scale, these works can be categorised in to three major categories: 1) double auctions 2) Vickrey Auctions 3) conventional first price auctions. We discuss a comprehensive overview of these technical works from perspective of green design requirements in this section. From perspective of design requirements, certain technical works tried to address one or more design requirement in order to enhance the green aspect in their decentralized energy auction. In this section, we provide an in-depth analysis of these works from green perspective. Apart from discussion, a detailed table highlighting the contribution and addressed design requirements, and other technical parameters have been presented in Table. III.

A. Double Auction

In a double auction mechanism, buyers and sellers submit their bids and asks in order to find a hammer price, which is further used to determine the total number of sold energy slots. Firstly, sellers submit their asking price which is arranged in an ascending order, afterwards, buyers submit their bids, which is arranged in a descending order. Once asking price and bids are collected, then the aggregated curves for demand and supply are generated and mapped over each other to find the intersection point. The intersection point is used to determine the hammer price of double auction, which is further used to find out the winning buyers and sellers [47]. A double auction mechanism is said to be incentive-compatible, when by acting on the preferred bids and asks, each buyer and seller gets their best outcome. Therefore, while developing double auction based energy trading mechanisms, researchers tend to integrate the functionality of incentive compatibility in their mechanisms. We divide this section of double auction into four sub-sections on the basis of incorporation of green design requirements in these works.

1) Efficient Auction Mechanism Design: Enhancing efficiency of double auction by reducing the convergence time is a critical step towards designing of green double auctions for decentralized smart grids. Till now, two works have been carried out by researchers that focused over reducing the iteration of energy auctions in order to converge them quickly as compared to traditional double auction. One such work in the direction of efficient auction design has been carried out by Kang *et al.* in [23], where authors work over enabling P2P energy trading for grid connected EVs using efficient double auction mechanism. Authors used the phenomenon of flag and trigger to solve the complex iterative problem of double auction in an optimal way. The proposed mechanism uses less iteration to converge, which in turn save excessive usage of energy during iteration process. Furthermore, the work also used consortium blockchain to overcome computational scarcity issue for the nodes which do not have significant computational resources. Another work discussing quick converging double auction

TABLE III
TECHNICAL WORKS IN BLOCKCHAIN BASED GREEN SMART GRID AUCTIONS.
ACRONYMS: SOCIAL WELFARE (SW), INDIVIDUAL RATIONALITY (IR), EQUILIBRIUM (EQ), TRANSACTION COST (TC), ENERGY CONSUMPTION (EC), ENERGY DEMAND (ED), SMART CONTRACT (SC), NOT SPECIFIED (N/S).

Auction Type	Addressed Green Issue	Ref.	Major Contribution	Type of Design Requirements Met	Blockchain Type	Consensus Mecha-nism	Auction Objectives Met						
							SW	IR	EQ	TC	EC	ED	SC
Double Auctions	Efficient Auction Design	[23]	Localized P2P energy trading for grid connected EVs.	• Auction Iteration Reduction • Reduction in Energy Consumption	Consortium	PoW	✔	✔	✔				
		[1]	Quick converging P2P auction for smart grid.	• Auction Convergence • Energy Loss Reduction • Computation Overhead	Public	PoW	✔	✔	✔	✔		✔	✔
	Communication & Computation Cost Reduction	[24]	Multi-tier energy auctions for distribution grids.	• Scalability • Computational Cost	Public	Business Driven		✔	✔		✔		✔
		[25]	Field implementation of energy market in Switzerland.	• Communication Cost Reduction via Tendermint	Private (permissioned)	Tendermint		✔	✔				✔
		[26]	Proposed three approaches for energy trading.	• Computation Efficiency	Public	PoA		✔				✔	✔
	Transaction & Data Storage Efficiency	[27]	Multi & internal micro grid energy trading.	• Distributed Data Storage • Reduction in Transaction Volume	Public	N/S	✔	✔		✔	✔		✔
		[28]	First price, time first based double auction for microgrid energy trading.	• Improving Transaction Efficiency	Consortium	PBFT	✔	✔			✔		
	Enhancing Energy Cost	[29]	Power flow & multilateral energy trading via Ethereum blockchain.	• Detecting Overlimit Power-Flow to Manage Energy	Private	PoW		✔		✔			✔
		[30]	Decentralized load balancing for P2P energy trading.	• P2P Energy Cost Reduction	Public	N/S	✔	✔	✔		✔		
		[31]	Decentralized load balancing via energy markets.	• Managing & Trading Energy Locally	Public	Tendermint	✔	✔	✔		✔		✔
		[32]	Charging power quota based energy trading.	• Charging Stations Settlement via Power Quota	Private	N/S	✔	✔			✔		✔
		[33]	Selfish & helpful bidding strategy for residential DERs.	• Peak Load Reduction	PBFT	PBFT	✔	✔			✔	✔	✔
		[22]	Grid influenced P2P Energy trading via Stackelberg game.	Reduction in Peak Demand	Public	N/S	✔	✔	✔		✔	✔	✔
		[34]	Energy exchange and settlement procedures for energy trading.	• Balancing Energy Consumption & Production Ratio	Public	PoS	✔	✔		✔	✔	✔	✔
		[35]	Decentralized local energy trading to enhance sustainability.	• Enhancing Local Trade to Prevent Energy Losses	Public	PoI	✔	✔					✔
		[36]	Hybrid P2P and P2G energy trading.	• Cost Reduction via Hybrid Energy Trading	Public	N/S	✔	✔	✔				✔
		[37]	Reward enhancing transactive energy auctions.	• Local Energy Trading Enhancement	Public	PoW	✔	✔	✔				✔
Vickrey Auctions	Enhancing Energy Cost	[38]	Differentially private decentralized microgrid auction.	• Energy Reduction	Consortium	PoW	✔	✔					
		[39]	Quasi-ideal P2P transactive energy trading.	• Managing Market Surplus Energy	Public	PoC	✔	✔				✔	✔
Conventional First Price Auctions	Enhancing Energy Cost	[40]	Multi-microgrid based energy trading.	• Efficient Architecture Design	Public	N/S	✔	✔					
		[41]	Transactive energy exchange for EI based blockchain.	• Enhancing Energy Management via EI Concept	Private (permissioned)	PBFT	✔	✔				✔	✔
		[42]	Practical implementation of decentralized energy trading.	• Cost Reduction	Public	N/S		✔					✔
	Transaction & Data Storage Efficiency	[43]	Game-theoretic framework for V2G network.	• Tx Throughput • Scalability	Public	IoTA	✔	✔	✔		✔	✔	✔
		[44]	Sealed auction transactions for V2G network.	• Transaction Matching & Convergence	Public	PoA	✔	✔				✔	✔
		[45]	Blockchain + IFPS storage for energy trading.	• Enhancing Data Storage	Public	Multiple	✔	✔		✔	✔		✔
		[46]	DSM enhancing grid optimal auction.	• Scalability Enhancement	Public	N/S	✔	✔	✔		✔		
	Efficient Auction Design	[44]	Sealed auction transactions for V2G network.	• Transaction Matching & Convergence	Public	PoA	✔	✔				✔	✔

have been presented by authors in [1]. Authors designed a mechanism via which majority of energy demands can be met in short number time, which in turn reduces the converging time for double auction. Moreover, authors also enhanced energy losses and computation overhead by motivating peers to trade energy locally.

2) Communication & Computation Cost Reduction: Providing efficient communication and computation has always been an important objective while development of decentralized energy auctions. In order to do so, certain research have been carried out by researchers, one such work to provide energy efficient computation for multi-tier auction distribution grids have been carried out by authors in [24]. Authors used a business driven consensus mechanism to enhance computational factor along with providing a more scalable blockchain model for secure energy auctions. Similarly, from perspective of field implementation, a detailed study on blockchain based energy market of Switzerland has been presented by authors in [25]. The work discussed reduction of communication and computation cost by using Tendermint consensus instead of traditional consensus protocols. Another similar work that targets to reduce computational scarcity in blockchain based auctions have been carried out by authors in [26]. The work proposed three energy trading approaches for blockchain based smart grid and compared them on the basis of cost and effectiveness. Similarly, the authors also provided the comparison of these approaches from perspective of clearing price and clearing quantity.

3) Transaction & Data Storage Efficiency: Storing and managing auction data in an efficient manner is one major challenge that blockchain based energy trading nodes are facing right now because of the distributed nature of blockchain. Since blockchain works over the phenomenon of distributed ledger, therefore, every new transaction is stored over this ledger. Considering the resource capacity of participating energy nodes, it is important to design such auction mechanisms which utilize minimum space while storing transaction data. On such work discussing an important aspect of dealing with energy transaction from perspective of both internal and multi-microgrids have been addressed by Zhao *et al.* in [27]. Authors enhanced distributed data storage along with reduction in transaction volume in order to provide more sustainable blockchain network from the point of view of our design requirement of efficient data storage. Another work to improve transaction efficiency by using first price and time-based double auction for blockchain based energy trading have been carried out authors in [28]. Authors evaluated the phenomenon of enhanced of transaction efficiency at difference points and claimed that the proposed mechanism provides energy efficiency alongside providing transaction storage efficiency. Furthermore, the work also used consortium blockchain PBFT consensus to reduce computational consumption.

4) Enhancing Energy Cost: Among all design requirements, one of the most critical design requirement while developing of double sided energy auctions is to reduce energy consumption as much as possible. Researchers are doing this via various approaches, some worked over motivating users to trade energy locally, while others proposed hybrid mechanisms for this trade. In this section, we summarize all these from perspective of their particular contribution to reduce energy usage at grid or user level in blockchain based energy trading auctions. First work that evaluated power flow and multilateral energy trading via Ethereum have been carried out by Jin *et al.* in [29]. One of the major contribution of authors in this work from green perspective is detection of overlimit power flow to reduce energy losses. Similar to this, two works focusing over decentralized load balancing via energy auction have been carried out by authors in [30], [31]. In [30], authors reduced P2P energy trading cost by proposing an auction mechanism which works over three layered blockchain architecture including application, virtual, and physical layer. Similarly, in [31], authors proposed an approach to balance renewable energy generation locally via novel auction market design.

A unique work from perspective of power quota based energy auction over blockchain have been presented by Ping *et al.* in [32]. Furthermore, authors worked over development of energy efficient mechanism for charging station settlement. A work that analyses the behaviours of selfish and helpful buyers on residential RER auction have been presented in [33]. Authors developed efficient bidding based MCP management system which enhances DSM by reducing peak load from residential houses. Similarly, an extensive theoretical contribution utilizing the benefits of Stackelberg game in blockchain based double auction have been presented by authors in [22]. Authors proposed a grid-influenced game-theoretic approach to reduce energy usage in peak hours which in turn provides efficient DSM. Similarly, a works on energy exchange and settlement procedures have been carried out by Han *et al.* in [34]. Authors proposed a blockchain based trading architecture that works over execution of smart contract in order to balance energy consumption and production.

A similar work focusing over decentralized energy trading to enhance sustainability of smart grid have been carried out by authors in [35]. Authors motivated local prosumers and buyers to carry out local trade in order to prevent surplus energy losses. Another work focusing over hybrid P2P and P2G energy trading blockchain based double auction have been presented by researchers in [36]. In this work, authors focused over cost reduction by motivating the trend of hybrid energy trading rather than just P2P energy trading. Apart from traditional double auction, a work focusing over Bandit learning based energy trading have been presented by researchers in [37]. The work focused over using Bandit learning based double auction to enhance reward in transactive energy auctions in order to motivate maximum sellers to trade energy to the decentralized market.

B. Vickrey Auctions

Vickrey auctions are usually used to maximize social welfare of all participants, because they provide a strong game-theoretic guarantee that every participant will have a non-negative social welfare at the end of the auction process [48]. In blockchain based green energy auctions, Vickrey auction has been applied in two technical works and in both of them they applied VCG auction, which is an advanced form of Vickrey second price auction. In VCG auction, highest bidder wins but pays the harm its presence have caused to other participating bidders. A detailed discussion about theoretical aspect of VCG auction is out of scope of this article, interested readers are suggested to go study the work in [39]. Moreover, both of the works applying VCG auction in blockchain based energy trading focused over reduction of energy cost and consumption to enhance the green effect in trading.

1) Enhancing Energy Cost: The first work integrating differential privacy, VCG auction, and consortium blockchain for decentralized energy auctions have been carried out by authors in [38]. The given work enhanced buyers and sellers utility along with providing privacy preservation via differential privacy guarantee. In order to preserve energy and communication cost of all participating nodes, authors proposed the usage of consortium blockchain instead of public blockchain. By using this blockchain network, only the selected participants will be able to take part in consensus, which in turn save the computation cost for casual smart metering nodes. Another work over VCG auction based energy trading have been carried out by authors in [39]. The authors worked over quasi-ideal P2P transaction energy trading mechanism in order to manage market surplus energy via VCG auction mechanism. Authors proposed a mechanism to handle four types of energy trading mechanisms in parallel, via which users can trade in a parallel manner according to different type of energy requirement.

C. Conventional First Price Auctions

Apart from two major auction types (which are discussed in above subsections), certain other works used various other auctions or similar trading approaches such as ascending price auction, message broadcasting base auction, Ausubel clinching auction, etc. It is important to note that all of these works chose highest bidder as a winner. Based upon this understanding, we named the section as 'Conventional First Price Auctions'. The works in this section can further be categorized into three categories on the basis of integration of green design requirement, which are as follows:

1) Enhancing Energy Cost: In first price auction mechanisms, one of the major focus of researchers is to enhance energy cost in order to make sure that the proposed mechanism is suitable for energy constrained blockchain nodes. Plenty of works have been carried out to overcome this energy scarcity, one such work functioning on unified weight clearing to select hammer price for energy slots have been proposed by Li *et al.* in [40]. Authors designed an energy efficient architecture for smooth energy trading in multi-microgrid scenario. Similarly, another work that provides a thorough comparison between three auction strategies on the basis of tokens, supply-demand regulation, and energy consumption has been presented by authors in [41]. The work further used the concept of energy Internet with transactive grid to trade energy in local markets in order to prevent excessive energy losses. Similarly, another work that used traditional first price auction along with providing the practical implementation of decentralized energy trading have been presented in [42]. Authors presented an extensive case study of practical implementation that ensured reduction of energy cost as compared to traditional blockchain implementation.

2) Transaction & Data Storage Efficiency: Another green design requirement that have been addressed in first price energy auction works is enhancement of transaction size and data storage. A very detailed work from perspective of enhancing Tx throughout and scalability of blockchain based game-theoretic ascending price auction have been presented by Hassija *et al.* in [43]. Authors first provided a thorough architecture for grid-connected EVs energy trading, and then evaluated the proposed model by showing that the model enhanced transaction throughput and blockchain scalability. One significant work that integrated IPFS storage with blockchain of manual E-auction based energy trading have been presented by authors in [45]. The work developed a novel system model to show the interoperability of IFPS storage with blockchain, and afterwards authors provided simulation based experiments to show that the proposed model reduces latency, cost, and transaction time as compared to traditional approaches. Similarly, a work that uses Ausubel's clinching auction based energy trading to enhance DSM of smart grid have been carried out by authors in [46]. The work ensured that the proposed mechanism enhances scalability in order to run all blockchain operations in an efficient manner.

3) Efficient Auction Mechanism Design: Developing efficient auction mechanisms, which can be replaced with traditional first price auctions is an important step towards green energy auctions for blockchain. One such mechanism that works over the phenomenon of reverse auction to increase auction design efficiency have been presented by authors in [44]. This work also analysed EV auction based power trading mechanism for grid connected EVs. The proposed work enhanced transaction matching and quick convergence in order to utilize energy in the most efficient manner.

D. Summary and Lessons Learnt

Integrating decentralized blockchain with smart grid auctions have paved path for future grid networks in which users can trade their energy with full trust. However, integration of green aspects in blockchain based energy auction scenarios still require further research. For instance, the seven design requirements that we discussed in Section III have not been fully addressed in the works and only few works partially address these requirements. However, it is worthy to mention that the works involving double auction are more inclined towards meeting multiple design requirements. For instance, it can be seen from Table. III that a significant number of double auction articles worked over enhancing energy consumption cost in order to reduce the overall energy usage. Similarly, the second dominant aspect that can be found in double auction works is that they worked over enhancing transaction cost in order to reduce network communication overhead. Similarly, some other articles also worked over balancing of energy generation and consumption ratio in order to reduce the carbon footprint from fossil fuel energy.

From perspective of Vickrey auctions, only the aspect of energy cost reduction can be seen in the literature. One work involving Vickrey auction focused over usage of consortium blockchain for efficient consensus, while the other work managed market surplus energy in an efficient manner via Quasi-ideal trading. However, a work that purely addresses all design requirements of a green energy auction has not yet published from perspective of Vickrey auctions. Similarly, from perspective of conventional first price auctions, certain works tried to provide efficient energy consumption alongside enhancing transaction cost. Similarly, the focus of remaining of conventional first price auction works was to develop cost effective architecture and market design.

To conclude, overall, a trend of enhancing energy cost can be seen in among all three auction categories, however, the category of conventional first price auction dominates in designing of efficient transaction and data storage models. Therefore, if one is interested to design an application in which nodes have limited memory and can handle less data volume, then works in the category of first price auction can play their role. Contrarily, if one's application has nodes with good storage power and are more energy constrained, then works from double and VCG auction can play their role in such development.

V. Challenges and Future Research Directions

Development of green energy auctions for blockchain based energy trading also has certain challenges due to transparent and computationally complex nature of blockchain. In this section, we discuss certain challenges, open issues, and their possible future research directions from the perspective of green aspect integration in blockchain based energy auctions.

A. Energy Harvesting

Efficient usage of energy along with energy harvesting is one of the major design requirement that we discussed in Section III. Similarly, this aspect is also one of the most significant challenge that green blockchain energy networks are facing. Traditional energy harvesting devices use kinetic, solar, RF, or thermal energy as a source [49]. These energy harvesting devices are being used by IoT nodes to generate energy for communication and transmission [20]. However, contrary to IoT nodes, blockchain nodes require large energy to carry out communication especially at the time of consensus. This is because in blockchain consensus, a block goes through a lot of phases such as broadcast, verification, acknowledgement, approval, etc. In all these phases, block needs to be sent to all nodes via communication medium, which incur a lot of energy . Therefore, small energy harvesting devices are not capable to provide energy for this much extensive communication. Certain that carry out broadcasting via energy from energy harvesting devices have been carried out in the past [50]. However, a work purely focusing over broadcasting of blockchain via energy harvesting is missing. Therefore, design and development of such energy harvesting devices which are purely developed for the purpose of blockchain based energy grid needs more attention of researchers.

B. Integration of AI in Auctions

Machine learning is being applied to auctions in order to carry out various statistical operations, such as prediction of the outcome of auctions such as hammer price, or number of successful buyers and sellers [51]. Similarly, another use case of machine learning is to automate auction market in a decentralized way [52]. Moreover, deep learning is also being used to predict optimal revenue of an auction mechanism having fixed budget [53]. Since, carrying out machine/deep learning is a computationally complex task and certain times one need computers with high processing power in order to process large amount of data. Therefore, if one want to apply machine/deep learning with blockchain based auction, then he has to traverse through all blocks in order to get required information. Therefore, there is a need to design such machine/deep learning based prediction and analysis models which use minimal resources while fetching and training data from blockchain decentralized ledger. Some researchers worked over this integration of blockchain, auction, and machine learning [54], [54]. However, this direction of machine/deep learning for blockchain based energy auctions has huge potential which can be explored further.

C. Privacy Preservation in Green Blockchain based Energy Auctions

Blockchain based energy networks do also comes up with various privacy issues due to their transparent nature [55]. The data of transactions and trading is publicly disseminated on ledger in order to enhance trust, but this also raises various privacy concern. For instance, this data can be used by adversaries to carry out some malicious activities. Therefore, the works which consider development/integration of green aspect in blockchain based energy trading do also needs to consider overcoming privacy issues such as transactional and consensus privacy in order to reduce any prospective risk. Certain decentralized energy auction works considered integration of privacy preservation strategies [56]. However, this direction of private auctions require further exploration, as very minimal work has been carried out yet. For instance, one direction could be to preserve privacy of microgrids trading their excessive energy. Another direction could be preserving the privacy of bidding nodes which do not want to show their private valuations of energy trading. Similarly, optimized private consensus mechanisms can also be developed which should focus over preserving privacy of mining nodes alongside using minimal computational cost.

D. Dynamic Spectrum Access for Green Communication

Excessive communication cost is one of the major hurdle in development of green networks [57]. Plenty of researches have been carried out to overcome this communication cost curse [58]. One of the significant direction is the integration of dynamic spectrum access via cognitive radio technology in blockchain based auction networks. Certain works highlighted the integration of cognitive radio with application of blockchain [59]. However, a work that purely targets cognitive radio based auction communication for decentralized smart grid has not been discussed in literature. Therefore, research can be carried out in this integration of blockchain based energy auctions with cognitive radio networks. E.g., blockchain nodes can serve as cognitive radio nodes and can take advantage from various functionalities of cognitive radio, such as using unlicensed spectrum at time of inactivity or using multiple channels to carry out auction communication, etc. Cognitive radio can be integrated with blockchain based auctions at various steps. However, the most significant integration will be to merge the functionality of cognitive radio during the decentralized auction consensus because communication overhead during consensus constitutes a major part of blockchain communication. Since cognitive radio will allow blockchain users to access unlicensed spectrum during idle times, it will save a massive communication overhead. Similarly, blockchain based auctions can also take the advantage of multiple channel functionality of cognitive radio to provide efficient communication. E.g., collection of bids and asks can be done via separate channels to avoid any congestion in the network. Via this integration, auction, consensus, and communication of blockchain based energy auctions can be carried out in an efficient manner.

VI. Conclusion

Blockchain based energy auctions is a novel paradigm in energy trading, and it has been discussed by many researchers due to its numerous benefits such as transparency, trust, etc. A lot of work have been carried out by researchers to enhance to integrate blockchain with energy auctions. No doubt, blockchain based energy auctions are beneficial in many ways, but it also faces a serious challenge of communication and computational scarcity because of its consensus feature. As in order to maintain a uniform blockchain state, every node has to update its ledger in an even manner, which is usually done by utilizing a lot of communication and computational power. Therefore, these issues give birth to another dimension named as 'green aspect' in blockchain based energy trading. In this article, we highlighted the need of green aspect in blockchain based energy auctions, then we highlighted certain design requirements which needs to be considered while development of such auctions. Afterwards, we analysed various technical works that has been carried out in this domain. Finally, we demonstrated certain challenges and possible future research directions for green integration in blockchain based smart grid auctions.

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