APPLICATION OF BLOCKCHAIN TECHNOLOGY IN ENERGY TRADING

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ABSTRACT

Proliferation of Renewable Energy Sources (RESs) and Electric Vehicles (EVs) is an important step towards sustainable transformation of energy sector ensuring access to affordable & clean energy and taking action to mitigate climate change. Studies report well designed Peer-to-Peer(P2P) energy trading models which benefit both energy consumers and prosumers are a new way of encouraging the use of these RESs and EVs. However, these local energy trading models can have trust, privacy and information security challenges which can hinder their adoption. Against this backdrop, blockchain technology has emerged as a promising technology which is capable of enabling P2P energy trading while addressing most of these issues. This paper presents the state of art of blockchain technology in the area of energy trading of the RESs and EV charging. Initially, this paper presents the current transformation of the electricity sector and how that relates to the sustainability and conservation of environment. Then it surveys the blockchain based energy trading models used in RE trading and EV charging by categorising them according to the type of blockchain (based on data privacy level requirement) and the consensus mechanism used. Finally, the challenges that needs to be addressed to facilitate widespread use of blockchain in energy trading are identified and hence some future research directions to pursue are proposed.

KEYWORDS _ *Blockchain, Electric vehicles, Peer-to-Peer energy trading, Review, Sustainability*

INTRODUCTION

Sustainable energy systems are required for meeting the needs of present without jeopardising the energy needs or climate of future generations. According to the Paris Agreement 2015, to limit the adverse effects of global warming, the global temperature increase should be hold well below 2°C by the end of this century, when compared to the pre-industrialised levels (United Nations, 2015). Further, according to the United Nations Key Sustainable Development Goals towards 2030 Agenda taking stepped-up efforts in ensuring access to affordable, reliable, and sustainable energy for all by progressing in energy efficiency (Goal 7) and to combat climate change and its impacts (Goal 13) are need of the hour(United Nations, 2016). Based on SDGs, many countries have introduced strict targets to reduce the Green House Gas (GHG) emissions, which are the major culprit of this global temperature increase. European Union set targets to significantly reduce GHG emissions by 2050 achieving net zero emissions while UK has committed to GHG emission reduction by 28% by 2035 and moving to net zero by 2050 (UK Government, 2021).

In accomplishing these environmental targets, transportation sector and the energy sector should be given priority since their proportions in total GHG emissions are the highest among industrial sectors (Nguyen, 2020). For instance, transportation sector accounts for more than one fourth of the GHG emissions in the UK and in Europe (Alvaro-Hermana et al., 2017). This highlights the requirement of encouraging the use of EVs to decarbonise the transportation sector. In addition, shifting from fossil fuel powered large powerplants to distributed energy systems based on RESs reduces the emissions related to energy sector. Therefore, studied suggest using environmentally friendly technologies like RESs and EVs can be a potential solution to climate change problem(Tushar et al., 2019). Despite the environmental benefits of these RESs and EVs, their widespread use among households is hindered due to the higher capital cost and lack of financial incentives. To facilitate the transition towards this distributed generation, the concept of energy prosumer has emerged, which refers to the participants who are able to both generate and consume energy (Silva et al., 2019). Therefore, design of local energy market models that provide various promising advantages for all participants: prosumers, consumers, and Distribution System Operators (DSO) are required to facilitate rapid proliferation of RESs and EVs in the power grid (Fernandez et al., 2021). In such background, Peer-to-Peer (P2P) energy trading (ET) models that facilitate direct ET between energy prosumers and consumers are proposed (Han et al., 2020, Huang et al., 2020).

P2P energy trading is a new ET agreement among energy consumers and prosumers in a distribution system (Silva et al., 2019). This enables prosumers to trade the surplus energy in their small scale DERs locally. P2P ET model has been widely discussed for ET among households (Ableitner et al., 2020, Alam et al., 2019, Kusakana, 2020, Etukudor et al., 2020) and among EVs (Alvaro-Hermana et al., 2017, Sun et al., 2020, Xia et al., 2020) due to the benefits such as reduced energy consumption cost (Khalid et al., 2020), increased prosumer monetary benefits (Kusakana, 2020) and decreased transmission losses (Ahmed and Kim, 2018). However, when the number of market participants (prosumers and EVs) increase, the systems should be capable of maintaining privacy and information security of end user data (Huang et al., 2019, Haputhanthirige et al., 2023). Centralised approach, which is one of the proposed solutions to address the security problem of ET, relies on a trusted third-party suffering from high information maintenance cost, single point failure and users' privacy leakage (Kang et al., 2017, Afzal et al., 2020). Therefore, secure decentralised ET mechanisms are proposed in literature and the potential of blockchain technology in ensuring the privacy and user information security in ET has received significant attention in research. Against this backdrop, this paper presents the blockchain based ET models proposed for household RE trading and EV ET (charging) and categorises them according to the type of blockchain, consensus mechanisms used and discusses the potential challenges and future research directions of blockchain based ET models to successfully achieve SDG targets and net zero targets.

BLOCKCHAIN BASED ENERGY TRADING MODELS STUDIED IN RE TRADING AND EV CHARGING

Blockchain technology which is defined as the "first native digital medium for peer-to-peer value exchange" (Park et al., 2018a) is one of the leading technologies which has the potential to fundamentally transform a wide range of markets and industries (OECD, 2023). Although it was originally designed for cryptocurrency verification in trading Bitcoin, it has gained higher popularity in other fields like economics, real estate, health care, legal sector and P2P ET in transferring centralised systems into decentralised systems(Mengelkamp et al., 2018b). Blockchain is one of the Distributed Ledger Technologies (DLTs) that records transactions between two parties efficiently and in a verifiable manner(Han et al., 2020). Blockchain's property of immutability makes it suitable for transaction validation as opposed to the centralised systems managed by a trusted single authority. Therefore, in ET, blockchain offers a secure, decentralised, and trustful platform that facilitates P2P energy transactions without requiring third parties to facilitate them.

After the creation of Bitcoin in 2008 by Satoshi Nakamoto, Mihaylov et al. (2014) was one of the first work to consider blockchain's work in ET by introducing the NRGcoins to trade RE. The below figure 1 shows the number of documents per year for the keyword search of TITLE-ABS-KEY ("Blockchain" OR "bitcoin") AND TITLE-ABS-KEY ("energy trad*" OR "energy market" OR "power market") in Scopus database. This depicts how the topic of the role of blockchain technology in the field of ET has received the attention in academia followed by the work of Mihaylov et al. (2014).

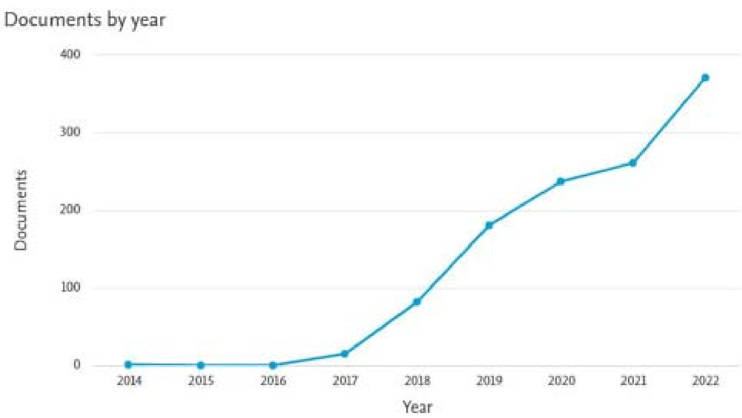

Figure 1: Scopus database searches for Blockchain and Energy Trading

Subsequent to the work Mihaylov et al. (2014), academia mostly focused on specific characteristics of blockchain based energy markets (Mengelkamp et al., 2018b), testing the applicability of blockchain technology via Proof of Concept implementation in small scale electricity markets (Sikorski et al., 2017) and designing blockchain based local energy markets (Mengelkamp et al., 2018a, Wang et al., 2017). Despite the ongoing development of academic research, industrial projects like Brooklyn Microgrid(Breuer, 2018): first real world project which facilitated blockchain based P2P trading, Share & Charge (CISION PR Newswire, 2017) started pilot testing blockchain based ET in real world. Following that, the research on blockchain based ET has taken off as evident from the figure above. Summarising the key works, this paper provides an overview of the blockchain based ET models for EV charging and P2P ET. Before that, this paper outlines some of the blockchain concepts related to classification of the models proposed.

Types of blockchain

According to the different needs of practical applications and the blockchain ownership, there are three main types of blockchain: public, private and consortium blockchain (Bhushan et al., 2020, Wang et al., 2019). Detailed characteristics in types of blockchain are presented in the table below.

Table 1: Comparison of types of blockchain

	Public Blockchain	**Private Blockchain**	**Consortium Blockchain**
Description	Permissionless network which allows anyone to join and participate in its core activities.	Type of blockchain technology in which the network is controlled by a single organisation or an entity.	A type of public & private blockchain which combines the best of both.
Participants	Anyone can participate on the network as a node.	Only verified participants can join the network. Validation must be done by a blockchain owner, or a set of rules declared by a blockchain owner	Only accessible to selected members.
Permission Authorisation	Anyone can validate blocks	One organisation	Selected authority nodes control access and consensus.
Structure	Decentralised	Centralised	Partially centralised
Advantage	Does not have access control.	Higher scalability. Lower energy consumption levels. Faster. Easily implementable	Low latency Higher scalability and security than public blockchain. Lower energy consumption levels.
Disadvantage	High network latency. Higher energy consumption levels. Scalability issues.	Less trustworthiness. Less decentralised. Has access control.	Lower level of transparency. Lower level of decentralisation.
Areas of application	Suitable for exchanging cryptocurrencies and mining.	Suitable for data management within organisations.	Best suited for organisational collaborations.

Sources:(Abrol, 2022, Teufel et al., 2019, Jiang et al., 2020)

In terms of structure, public blockchain, private blockchain and consortium blockchain are completely decentralised, completely centralised and partially centralised respectively. Public blockchain which facilitates any individual to join and participate in the mining process: the process of validating blocks in the blockchain, generally has a higher energy consumption and lower efficiency. In contrast, private blockchain use selected individual/ group of participants to control the mining process showcasing lower energy consumption and higher efficiency (Bhushan et al., 2020). Consortium blockchain which is presented as a merge of both public and private blockchains use pre-selected authority nodes to consensus and control access providing higher efficiency and lower energy consumption along with more security and scalability.

Consensus mechanisms

Given that there are no central authorities to manage transactions in blockchain based energy markets, all prosumer nodes must agree upon an energy transaction before storing that into the blockchain (Siano et al., 2019). The validity of the newly created transaction blocks depends on the whether the consensus has been reached among all the participating nodes. There are number of consensus mechanisms in blockchain systems which are configured to determine how new block is added into the blockchain as summarised in the table below.

Table 2: Comparison of consensus mechanisms

Consensus mechanism	**Description**	**Advantages**	**Limitations**
Proof of Work (PoW)	Use mining process which is used by the entities present in the network to authenticate when a new transaction arrives in the network by solving a puzzle.	Best option as far as private data safety is concerned.	Higher energy footprint and latency. Cannot directly use for energy transactions.
Proof of Stake (PoS)	Validators who have a higher stake at the cryptocurrency (more cryptocurrency) are selected for block validation.	More energy efficient. More scalability.	Not secure as much as PoW. A rich get richer.
Proof of Authority (PoA)	Nodes with particular keys can act as validators with the authority to create and protect the chain acting as authorities to protect the chain. Generally, in private/consortium blockchain.	Lower latency. More secure. No need of large number of tokens to qualify as validators.	Reputation cannot always keep participants from malicious actions. Lower efficiency.
Delegated Proof of Stake (DPoS)	A representative democracy: nodes select specialized nodes and delegate them to generate and verify the blocks. If these selected nodes fail to perform their duties, they will lose this right.	Lower energy consumption than PoW. Faster confirmation speed than PoW.	Increased possibility of error. May cause abusing delegate's rights.
Practical Byzantine Fault Tolerant (PBFT)	Consensus can be reached when the number of Byzantine faults (malicious nodes) is less than one-third of the total number of nodes. Suitable for small networks, consortium blockchains or private blockchain.	Lower energy consumption, system cost. Higher throughput compared to PoW, PoS, DPoS. Members of the blockchain are partially trusted.	More accurate only when the number of malicious nodes is less than 1/3. Suitable for low-latency storage systems that do not require large data throughput.
DPOSP	Improvement of PBFT and DPOS as a new consensus algorithm, which needs less power and computing resource for mining.	Reduce resource consumption. Enhances consensus efficiency. Support fast transaction payments.	
Proof of Benefit (PoB)	Validates transactions based on the benefit that they bring to the network. Designed to accommodate a large volume of electricity orders from the public and confirm the transaction to extend the blockchain.	Higher scalability. Effectively prevents Sybil nodes becoming validators. Saves computational power & lower latency compared to PoW.	Measuring the benefit of a transaction can be subjective.
Proof of Energy (PoE)	Simplified version of PoS where validator is chosen to be the prosumer with the best self-consumption ratio.	Promotes energy efficiency and sustainable behaviour.	
Proof of Work based on Reputation (PoWR)	Direct trust rating is used-candidates that have the highest reputation rankings in PoWR imply a higher degree of trust.	Reduced block creation time and computational costs. Reduced malicious activities during consensus process.	Approach may not be completely decentralised.

Sources:(Siano et al., 2019, Ahl et al., 2020, Agung and Handayani, 2020)

Proof of Work which was initially introduced as the consensus mechanism in Bitcoin blockchain(Ahl et al., 2020) involves higher energy consumption and latency. As an improvement for that, consensus mechanisms like PoS and PoA were proposed with lower latency and resource consumption. Further, PBFT which is mostly used in consortium/ private blockchain can provide higher throughput while tolerating Byzantine failures. Furthermore, modified consensus mechanisms like PoB (Zhang et al., 2021) and PoE improves energy efficiency and sustainability along with lower latency.

Blockchain based energy trading models for EV charging and RE trading classification.

Within the context of this research, ET in the EVs refers to charging EVs via plugging into the grid in charging stations and via vehicle-to-vehicle charging. In terms of RE, ET refers to local ET among households within a community/ a microgrid or ET among microgrids. The blockchain based models proposed in the literature for EVs are categorised according to the type of blockchain and the consensus mechanism and can be presented in the table below.

Table 3: Summary of blockchain based energy trading models proposed for EV charging.

Reference	Contribution	Type of Blockchain	Consensus mechanism
Sun et al. (2020)	V2V ET in social hotspots to optimise social welfare using iterative double auction	Consortium	DPOSP
Zhang et al. (2021)	Propose a public electric power exchange service network with a gateway-based privacy-preserving scheme to implement authentication and data encryption for EV charging and discharging from grid peers.	Public	PoB
Kang et al. (2017)	Propose a localized peer-to-peer (P2P) electricity trading model for locally buying and selling electricity among plug-in hybrid EVs (PHEVs) in smart grids based on local aggregators.	Consortium	PoW
Huang et al. (2019)	Propose optimal charging scheduling algorithm for hybrid vehicle charging scenarios.	Consortium	PBFT
Chaudhary et al. (2019)	Presents a BC based secure ET scheme for EVs.	Consortium	PoW
Umoren et al. (2020)	Presented an ET system where EVs and critical consumers trade energy with respect to demand–supply mismatch	Private	PBFT
Jindal et al. (2019)	Presents a Blockchain based Edge as-a-Service Framework for Secure ET in software defined networking (SDN)-enabled V2G Environment.	Not specified	PoW
Silva et al. (2019)	Implementing ET platform for EVs in a smart campus parking lot using Hyperledger Fabric, where participants, assets, transactions, and events were defined and discussed.	Private	Not specified.
Long et al. (2020)	Propose a decentralized blockchain-enabled ET scheme which enables reliable transactions between EVs and energy nodes within short processing delay.	Consortium	3 phase approach
Chen and Zhang (2019)	Propose an innovative interdisciplinary work to implement the energy blockchain-based safe electricity trading and incentive contract model for EVs.	Consortium	PBFT

As depicted in the table above most of the work are focused on designing and testing blockchain based secure ET models for EV charging in social hotspots (Sun et al., 2020) and smart grids (Kang et al., 2017). Consortium blockchain is the most widely used type of blockchain in the proposed models whereas PBFT is proposed most of the times with the consortium blockchain based models due to its properties of lower latency, higher throughput, and support to larger scale traceability. Similarly, the classified blockchain based ET models for household RE trading can be presented in the table below.

Table 4: Summary of blockchain based energy trading models for renewable energy trading models.

Reference	**Contribution**	**Type of Block-chain**	**Consensus mechanism**
Mihaylov et al. (2014)	Introduce a new decentralized digital currency NRG-coin allowing prosumers in the smart grid to trade locally produced renewable energy.	Public	N/A Proposed NGR coins
Ableitner et al. (2020)	Practical implementation of the P2P energy market among households as a time-discrete, iterative double auction.	Consortium	PoS
Jiang et al. (2020)	Proposing a game theory-based pricing model in a localized PBFT-CB.	Consortium	PBFT
Foti and Vavalis (2019)	Study how the technology of blockchain may enable the instant trading of solar energy between neigh-bourhoods while presenting the design, prototype implementation, and the analysis of a decentralized, real-time, uniform-price double auction energy market.	Consortium	PoA
Yahaya et al. (2020a)	Propose a Local Energy Markets (LEMs) within a small community with many photovoltaic systems considering both home energy management and demurrage mechanism simultaneously.	Private	PoW
Yahaya et al. (2020b)	Proposing a blockchain based secure Demand Response Management model for ET and load balancing in a smart grid ecosystem.	Consortium	PoWR
Mengelkamp et al. (2018a)	Derive seven components for the efficient design and operation of blockchain-based microgrid energy markets to locally trade distributed generation.	Private	Identity based mech-anism
Han et al. (2020)	Presents a universal framework for a blockchain platform that enables P2P ET in the retail electricity market.	Private	PoS
Wang et al. (2017)	Proposing a direct electricity transaction mode between Distributed Generations and consumers in a microgrid based on continuous double auction (CDA)	Public	PoS
Ahl et al. (2020)	Blockchain based P2P microgrid case in Japan is analysed from technological, economic, social, environmental, and institutional dimensions.	Private	PoA
Thakur and Breslin (2018)	Blockchain based distributed coalition formation algorithm for Microgrid energy trade.	Both public and private	PoW
Afzal et al. (2020)	Blockchain implementation of the ET among mul-tiple homes in community microgrid using smart contracts.	Public	PoS
Park et al. (2018b)	Propose a BC based P2P energy transaction plat-form for ET between smart homes.	Not specified	Not specified
Siano et al. (2019)	Attempts to establish the baseline for a reference framework for blockchain-based Transactive Man-agement Infrastructure that can be used by medium sized aggregators to manage LEMs.	Private	PoE

In terms of RE trading authors have focused on proposing new digital currencies (Mihaylov et al., 2019), Designing and testing blockchain based ET models and platforms for microgrid (Wang et al., 2017) and community et (Afzal et al., 2020, Yahaya et al., 2020b) and real world implementation of blockchain based ET models (Ableitner et al., 2020). Authors have mostly proposed private/ consortium blockchain and different consensus mechanisms based on the requirements of the models designed.

CHALLENGES RELATED TO WIDESPREAD USE OF BLOCKCHAIN IN ENERGY TRADING

Despite all the benefits of blockchain technology in ET, still there are several challenges and drawbacks that needs to be addressed to promote the widespread use of blockchain technology in the industry of ET. According to Ahl et al. (2020) these challenges are multifaceted including technological, economic, social, environmental, and institutional challenges which are interrelated. Therefore, the analysis of these challenges requires a holistic and multi-angled approach.

According to the work (Mika and Goudz, 2020, Brilliantova and Thurner, 2019) the major concerns in the blockchain based energy sector does not only include technical concerns, but also the regulatory concerns. In terms of technical issues, the most significant weakness of blockchain based ET is the scalability of blockchain solution which is referred to as “its ability to improve with the growth of the resources” (Mika and Goudz, 2020). In particular, public blockchains are not matured enough to handle large number of transactions causing different performance issues such as lower throughput and higher latency. In terms of regulatory concerns, lack of applicable systems of laws, regulations and statutory guidance is a significant challenge for wide adoption of blockchain based systems, especially in large companies. On the other hand, these regulatory and technical concerns are interrelated with the social, economic, and environmental challenges. For instance, some of the most widely used consensus mechanisms like PoW are associated with higher energy consumption and hence higher carbon footprints leading to environmental concerns(Wang et al., 2019). Further, public acceptance and user participation of the novel blockchain based systems is highly challenging and dependent of the high transaction costs caused by the regulatory hurdles that prevent them from entering the market. Furthermore, some of the technical properties of blockchain prevents deletion and “to be forgotten” of the data, which is a key demand of the basic data protection regulation (Mika and Goudz, 2020). By modifying the categorisation in Ahl et al. (2020) all the challenges identified in the blockchain base ET are categorised in to five categories: technical, social, environmental, economic and legal and presented as in the figure 2 below.

CONCLUSIONS AND FUTURE RESEARCH DIRECTIONS

Blockchain technology has been developed through several stages and has been applied into various fields due to its properties of decentralisation, immutability, privacy, and information security. As presented in this study, from the perspective of ET, blockchain technology is still in the early stages but is making a great progress in solving the limitations of traditional energy markets. However, these theoretical applications are still very difficult to implement due to the challenges discussed in section 3. Therefore, as promising as this technology looks, the necessary actions should be taken to address these challenges to ensure the widespread use of this technology in ET in the foreseeable future. In particular, the intertwined technical, social, environmental, legal, and economic challenges should be addressed using a holistic approach with practitioners, academics, and industry-academia collaboration in the energy sector.

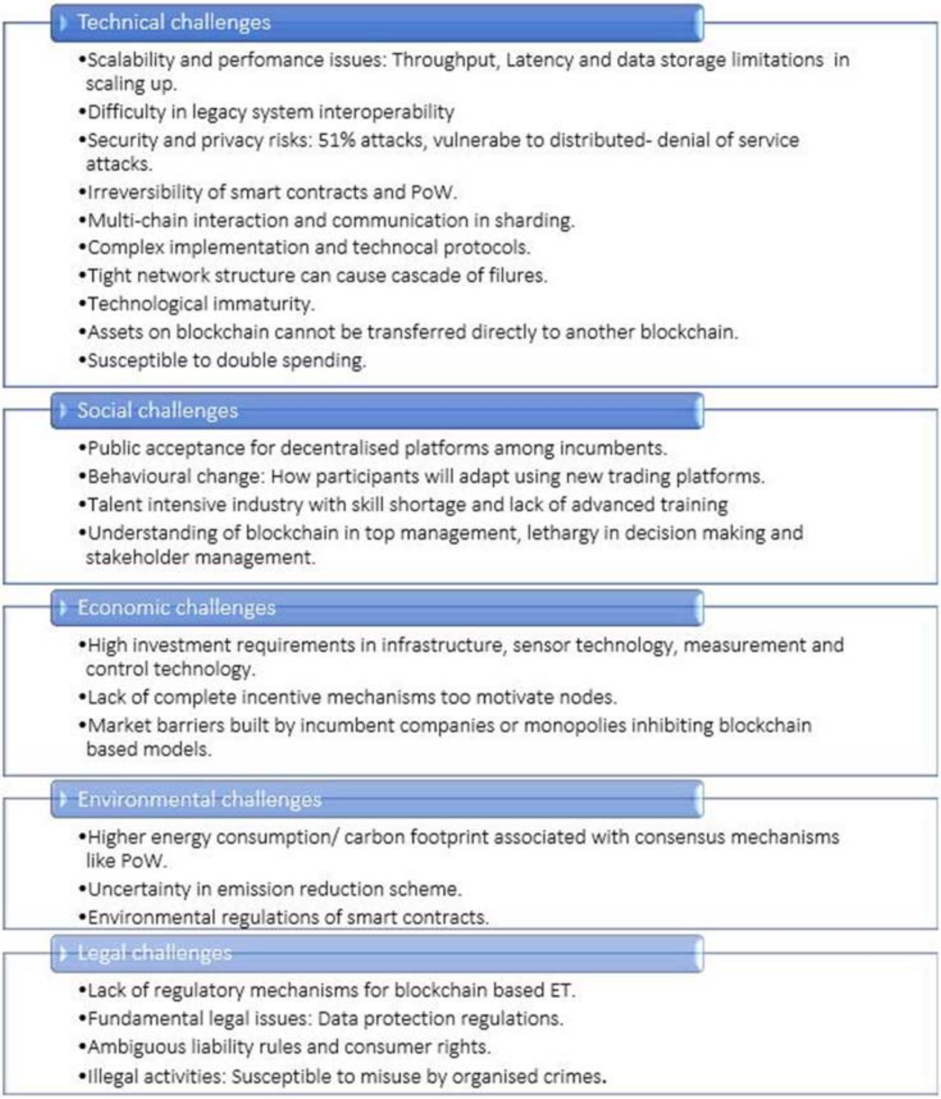

Figure 2: Classification of challenges for blockchain based energy trading models.

Some of the future research directions to be considered in advancing blockchain based ET models for EVs and household RESs can be listed as below.

- Improvement of scalability and performance (latency and throughput) of blockchain based ET systems.
- Proposing energy certifications to differentiate between green energy and brown energy (which is cheaper) producers to discourage selling the fossil fuel-based energy and to encourage using green energy.
- Improvement to the scalability of blockchain based solutions using sharding mechanism to reduce data redundancy and storage space so that it can be implemented in wider scale energy communities.
- Studying multi-chain interaction and communication in sharding.

- Improvements of consensus mechanisms to propose less energy intensive and faster consensus mechanisms.
- Developing systems and frameworks of laws and regulations to balance privacy protection and regulation.
- Large scale experimentation via testing the scalability of decentralised real-time energy applications when the number of prosumers/ the EV users in the system significantly increases.
- Studying interoperability and standardisation of different blockchain systems in designing blockchain based ET models.
- Designing effective incentive mechanisms to encourage more user (prosumer node) participation.
- Developing and testing platform business models to facilitate blockchain based ET.

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