Blockchain Enabled Smart Metering Solutions: Challenges and Opportunities

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2022 22nd National Power Systems Conference (NPSC) | 978-1-6654-6202-0/22/$31.00 ©2022 IEEE | DOI: 10.1109/NPSC57038.2022.10069901

Abstract— **The applications of smart energy meters have been increasing in power systems, such as real-time monitoring, remote control, online billing, theft detection, energy trading, energy forecasting, and demand response by using the Internet of Things (IoT). IoT based smart metering system is centralized in nature, which has data security and privacy issues. Since blockchain is secured, authentic, confidential, and data integrity properties, hence blockchain enabled smart metering is an effective solution. This paper reviews a broad understanding of blockchain enabled smart metering systems and opportunities in various segments. This paper highlights the shortcomings in smart metering systems, which effectively address the privacy and security gaps, discusses blockchain-based energy trading and the existing pilot project of blockchain technology in India.**

Keywords—Blockchain Technology, energy trading, privacy, smart meter, security

I. INTRODUCTION

A smart meter is an electronic watt-hour device with bidirectional communication, data management, and internal connection/disconnection features. However, in the era of Internet of Things (IoT), It is used to measure the real-time energy of the system, record, monitor the data, and control the system remotely. It is helpful in online billing and theft detection. Smart meters generate a large amount of data used in various applications like load profiling, forecasting, demand response, pricing, and efficient energy production [1]. IoT based smart metering systems have various challenges like cybersecurity, scalability, data privacy, and interoperability. It also impacts economic regulation and market mechanisms, economic efficiency, risk aversion, trust, grid balancing, grid regulation, and insufficient data availability [2]. As energy demand is expanding, the adaption of renewable energy generation and the huge number of smart/IoT devices are exponentially increasing [3].

The smart meter generated data are sensitive because by analyzing a houses' electricity usage pattern, anyone may misuse that data against the house. There are chances of cyber-attack in which consumers have data security, privacy, and energy trading issues [4], [5]. These issues happen due to the injection of malicious data into smart devices, manipulating the data, or disturbing the balance between demand and supply [6]. In the whole process, secure transactions from malicious activities are needed. This malicious data also have bad consequences for the energy trading system [7]. To prevent the system from malicious activity, decentralized based blockchain technology is used.

Blockchain technology ensures that data is authentic, confidential, and integrity [7], [8]. It works on decentralized data and ensures that only authorized participants can access personal data [1]. So, transparency is present among the participants. This technology secures the data as well as is helpful in secure energy trading [6]. There is no need for a third party to trade among prosumers. Using this technology, prosumers can locally trade the energy surplus to consumers at a better price [9]. Blockchain helps the system to mitigate all the challenges of smart metering systems. It increases the prosumers' awareness, provides an optimized trading platform, enhances consumers' choices, clean energy tracking, a decentralized power market, and a screening technique for cybersecurity. The blockchain enables many uses where transparency, clean energy tracking, and renewable energy certification are necessary [10].

Blockchain is a growing area of research, and researchers are exploring the application of blockchain in smart metering systems in the wider domain. The smart meter is deployed internationally in which data security, privacy, and secure energy transaction are expected to enhance. It will lead to flexibility for the integrated future power system. This paper reviews the blockchain enabled smart metering solution and their applications in different segments and identifies the shortcomings in the smart metering system and opportunities in various segments. The contribution of this work is to discuss and enumerate the smart meter, blockchain technology, concepts of blockchain in smart metering, challenges, and opportunities. Based on the literature review, various applications in future areas are also discussed. There are need to explore wider blockchain applications in the smart metering system. It explains all about the evolving applications of the blockchain and where it can be used and discusses the project existing in India.

The paper is organized as follows: Section II explains smart meters' data security and privacy using blockchain technology. Section III introduces blockchain based energy trading using smart meter data, and Section IV discusses about the challenges. Section V explains the opportunities and existing projects in India. Section VI concludes the paper.

II. BLOCKCHAIN BASED SMART METERS' DATA SECURITY

Smart metering systems involve many essential data, consumers' energy supply decision making, and energy bills depend on it. Protecting that data from tampering and leakage is very important to reduce the economic losses. The smart meter real time data remote monitoring, controlling are offering by IoT, which is a centralized type of system. So, there is a chance to compromise data if the malicious actors get that data. It manipulates the data and financial impacts, like overpaying customers and losing the utility. Smart energy systems have security issues in energy IoT data analytics, energy theft, attacks on smart homes, cyber-attack on the electricity market, and transactive energy systems [11]. To mitigate these issues, it is essential to control the cyber threat, reduce the possible impact of the connectivity routes, reduce IoT device

This work is supported by Science & Engineering Research Board (SERB), DST (File no. SPG/2021/004202) and MHRD (India) grants for SPARC Project #1317

978-1-6654-6202-0/22/$31.00 ©2022 IEEE

vulnerabilities, and have a lightweight intrusion detection system.

The IoT based smart metering data management system is centralized in nature so, it is not reliable because, firstly, participants do not have access to it. So, transparency is not there, and secondly, the data admin may manipulate/change the data. There is a need to detect the tamper and prevention mechanism to implement an embedded and secured crypto mechanism. That is why a decentralized system comes into the picture, in which everyone has the authority of that system [12]. A decentralized system like blockchain has very hard to modify the data, so it is trustworthy. Blockchain have all these properties like tamperproof, decentration, traceability [13]. A decentralized based system has firmware protection, side channel protection, secure operating and update procedures. The applications programming interface are secure, and periodically secure testing mechanism [11].

A. Blockchain Technology

A blockchain is a decentralized accounting ledger that enables, manages, tracks, and verifies thousands of energy transactions per second. It aims to accurately track energy produced and turn it into portfolio energy credits. The smart energy meters' acquired data are unguarded by cyber attacks, which may impact the power system [14]. The attack may be external as well as internal [16]. There are various types of attacks, such as replay attacks, modification attacks, forgery attacks, and man-in-the-middle attacks [15]. To provide trusted data, enable secure Peer-to-Peer (P2P) energy trading, consumers' privacy, security, and stabilize the grid, blockchain technology is used. Several blockchain enabled smart metering applications are shown in Fig 1.

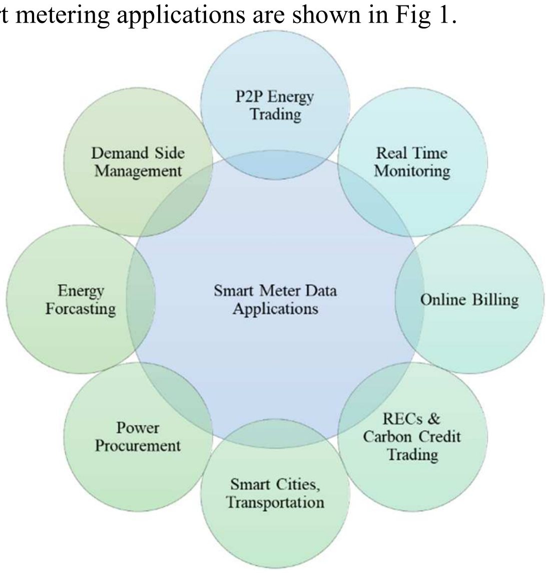

Fig. 1 Blockchain Applications

The basic terminologies of the blockchain are as follows:

1. *Smart contracts:* Smart contracts are digital based scripts or contracts kept in blockchain technology. It is self-executing according to their algorithms. It cannot be disconnected from the blockchain once it starts. So, it could not tamper. It is used in managing bids and offers, market clearing, financial transactions, computations, and contracting operations [17]. They access the values of control accounts and behaviors to improve the efficiency and security of the scheme. It avoids the existence of a third party [18].
2. *Hash:* The hash function can have any input length and a mix of alphabets, integers, media files, or other data and convert it into a fixed data length. That fixed length of the output is called the Hash. It has a unique number, and every unique number represents the identity of that block. The hash values are interconnected like the previous block's hash is saved to the current block, and the current block's hash value is stored in the next block.
3. *Consensus mechanism:* It ensures transactions' validation and authorizes a data block. The frequently used consensus mechanisms are Proof-of-Work, Proof-of-Authority, Proof-of-Stake, Delegated Proof-of-Stake, etc.

B. Blockchain Transaction Process

The blockchain's first step is storing some relevant data in a single block. For example, transaction information is stored in the case of bitcoin. It means different data is stored for different applications. The second step stores the hash value like a unique fingerprint. At the time of storing the data, the block generates a unique code, which is called the Hash. The previous block's hash value is saved to the current block, and the current block's hash value is stored in the next block as shown in Fig. 2. In this type, it forms a chain. The first block is called the "genesis block", and the whole process is called blockchain technology. It is easy to track the data as well as the unique identification of the information, and very difficult to manipulate the data. Blockchain is a secure and reliable technique [15].

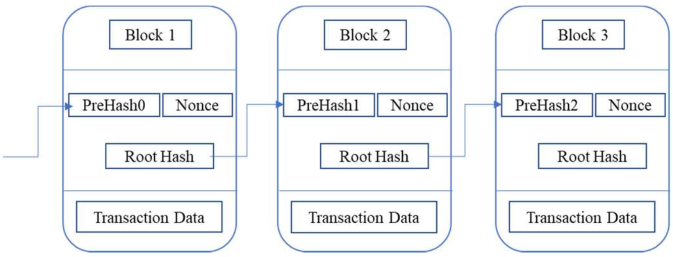

Fig. 2 Blockchain Transaction process

C. Types of Blockchain Technology

Blockchain is classified into four forms, public blockchain, and private blockchain, hybrid blockchain and the consortium blockchain. In public blockchain, everyone has access to participate and join the network's activity. It is difficult to hack, because higher network's size, more records, distributed. Every authorized nodes have a copy of digital ledger, so it is entirely open and transparent. While in private blockchain only authorized participants to have access to join the network's activity. It is typically utilized within a company or organization where only few people are allowed to participate in the network. Because of the fewer nodes than public network, the transaction per second rate is higher and one can customize the size of private blockchain to meet the specific requirements. Hybrid blockchain combines the advantages of private and public blockchain. Only a portion of data can be

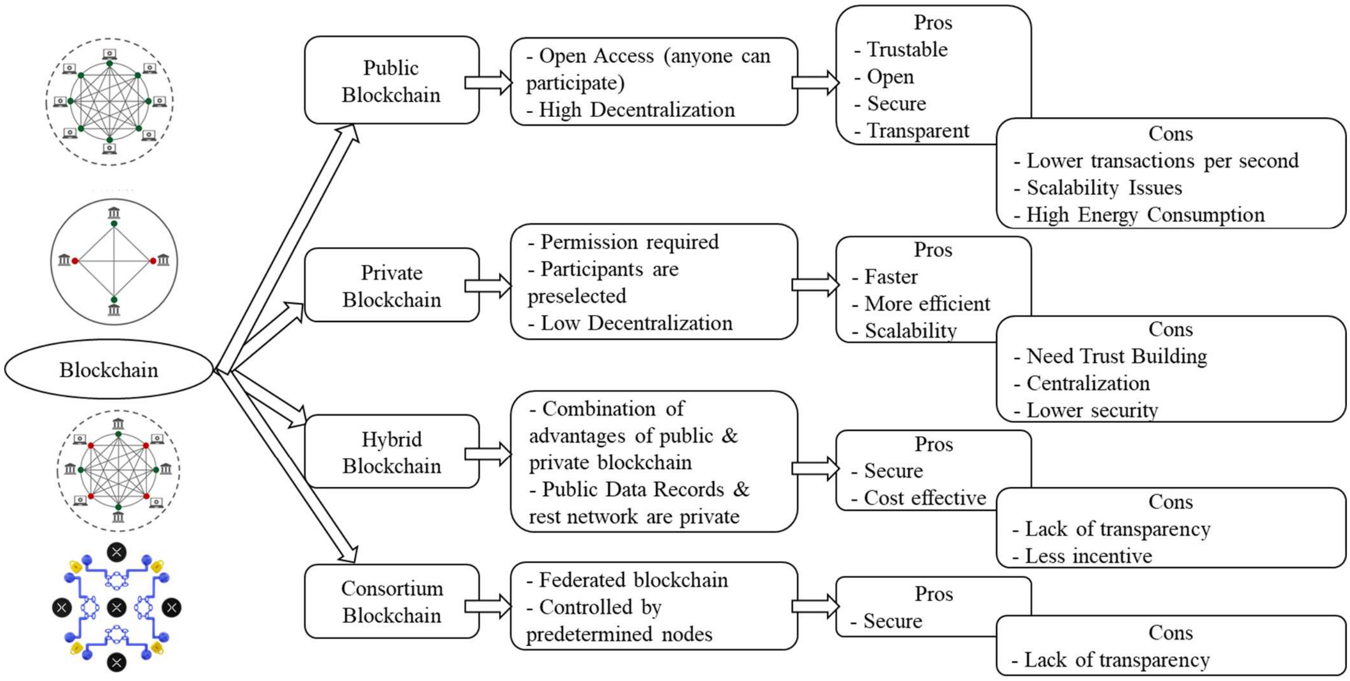

Fig. 3 Types of Blockchain

made public in the network, leaving rest of the network data private. It is more secure and cost effective, because it has scalability than public blockchain network and transactions are quick and inexpensive. Consortium blockchain are controlled by predetermined nodes. It has a validator node that is responsible for initiating, receiving, and validating the transactions as shown in Fig. 3.

D. Smart Meter Data Issues and Solutions

There are several issues regarding the secure transmission of smart meter data protection and privacy. The blockchain technology is used to solve these issues by using consensus algorithms, smart contracts, and asymmetric encryption. A consensus algorithm is used to check the block content consistency, affecting the performance of limited systems [19]. The comparison of smart metering systems with and without blockchain based on privacy and security parameters are given in TABLE I. To analyze the smart metering data issues in terms of security, privacy, and system structure are shown below:

- Smart metering systems involve the consumers' personal data and energy consumption details. Tampering or disclosure of that data can cause economic losses. To improve the smart meters' data security in transmission, blockchain technology is used [20]. To verify transmission data, encrypt, and sign, asymmetric encryption is used [19], [21].
- Suppose the cyber-attack happens on the energy consumption data. In that case, the attackers may capture the consumer behavior by analyzing the data and finding which type of appliance the consumer used and his privacy will exposed. For this issue hash encryption algorithm is used in blockchain technology. It hides the data content, data source, and another information. Data access is limited to enhance privacy, and control policy access [19], [22].
- The traditional centralized system faces many problems like flexibility, single point failure, and the processing of limited transaction performance. Blockchain technology ensures the general operation of the smart metering systems will not be disturbed due to malicious nodes or some faults. Blockchain technology adopts P2P network distribution, transmission storage, and consensus mechanisms. Transactional process efficiency is improved by deploying smart contracts [19], [23].

TABLE I: COMPARISON OF DATA SECURITY AND PRIVACY PARAMETERS WITH AND WITHOUT BLOCKCHAIN

Parameters	**Smart Metering System without Blockchain**	**Smart Metering System with Blockchain**
Immutability	Administrators have the ability to alter the data	The data can not be changed
Trust	Public trust issue	Acquires the public trust
Scalability	Very less options to expand the network	Large number of options & expand fast
Region	Depends on the regional authorities.	Easy access to the several regional authorities
Third party	Relied on third party	No third party involvement
Decentralization	Single point failure	Flexibility against single point failure
Availability & transparency	Administrators availability only	Accessible to every players
Heterogeneity	Limited applicability or in a particular domain.	Versatile and flexible in nature, can be applied in any industry
Security	Vulnerable to hack & data tampering	Secured by cryptography & consensus mechanism

III. Blockchain Based Energy Trading Using Smart Meter

In the current era, many consumers consume electric energy and produce it using distributed energy sources, called prosumers. If the prosumer has some extra power, they may sell it to the utility or the nearest consumer. So, it is possible that one can purchase electricity directly from their neighbor in the event of an emergency. For secure implementation, blockchain technology is used in which a consensus algorithm is required for integrity and availability among peers. It is needed to append any block to the ledger. Consensus provides good transaction latency, low computational resources, and high throughput [24]. These necessary services are also allowed to operate on such blockchain based microgrids. This type of system exists in Brooklyn, New York, where neighbors can buy power from one another in an open marketplace. This process can be done through a mobile application that sets a predetermined bid price for purchasing power for those who want it and sell it. Such efforts offer real time guarantees to consumers that the power is utilized from renewable sources. Prosumers are allowed to securely commercialize the extra electricity through blockchain technology [25]. Blockchain enables many use cases where transparency, tracking, and certification are necessary [10].

A. Methodology

The deployment of smart meters enables opportunity for the prosumers to sell the energy surplus using blockchain. Prosumers are able to see the total amount of energy production, consumption, energy demand, buyers, sellers, and prices [26]. For securely trading of the energy surplus the algorithm are as follows:

Blockchain based Energy Trading Algorithm [27]

1. Number of users for each time slot
2. Calculate the loss factor for each user, as given in (1)
3. Using the component of market management, calculate the bidding data
4. Send the request for the energy market price
5. To calculate the power and price, solve the marginal price of the end user as given in (2)
6. Acknowledge the energy market price
7. Send the request for a market commitment block
8. Unconfirmed transaction data stored in blockchain server
9. To approve the transactions, miners compete
10. Market data is approved by miners and stored as a block
11. Send the acknowledgment of the market commitment block

There are different terminologies used in the algorithm, which are given below.

Loss factor: $$\eta_{D_i} = \frac{\Delta P_{loss_i}}{\Delta P_i} \tag{1}$$

In (1) η_{D_i} is a loss factor for user i, ΔP_{loss_i} is a change in the system losses, and ΔP_i is a incremental change in power. For user marginal pricing, maximize the social welfare:

$$\max J = \sum_{i}^{D}\sum_{m}^{D_i}\left[PD_{i,m}\gamma_{D_{i,m}}(1+\eta_{D_i})\right] - \sum_{j}^{G}\sum_{k}^{G_j}\left[PD_{j,k}\gamma_{G_{j,k}}(1-\eta_{G_j})\right] \tag{2}$$

Balanced power constraints:

$$\sum_{i}^{D}\sum_{m}^{D_i}\left[PD_{i,m}\gamma_{D_{i,m}}(1+\eta_{D_i})\right] = \sum_{j}^{G}\sum_{k}^{G_j}\left[PD_{j,k}\gamma_{G_{j,k}}(1-\eta_{G_j})\right] \tag{3}$$

The marginal price is determined using power balanced constrained equations. After the market update, the end user and generator update the price based on the loss factor given in (4), (5), [27].

$$\lambda_{D_i}^{*} = \lambda(1+\eta_{D_i}) \tag{4}$$

$$\lambda_{G_j}^{*} = \lambda \tag{5}$$

Here, (i, m) is the identifying index of demand participants and blocks, respectively. (j, k) are the identifying index of distributed generators and blocks, respectively. The parameters $\gamma_{D_{i,m}}$ is the m^{th} block price for demand i, $\gamma_{G_{j,k}}$ is the k^{th} block price for generator j. $PD_{i,m}^{up}$ is the upper limits of power of block m for demand i, $PG_{j,k}^{up}$ is the upper limits of power of block m for generator j. In the above given equations the variables η_{D_i} is the loss factor for demand i, η_{G_j} is the loss factor for generators j. λ is the internal marginal price, $\lambda_{D_i}^{*}$ is the updated loss price for demand i, $\lambda_{G_j}^{*}$ is the updated loss price for generator j.

Energy deficit or surplus are traded on a forecast basis and then migrate to actual consumption and production [9]. Blockchain technology includes welfare optimization and cyber security [26]. The energy is securely brought to the prosumers by using their respective smart meter. The procedure to gather the data from their corresponding smart meter and create a block is done by a peer using the P2P network. Add that block into the blockchain using the consensus algorithm. In which consumer data acquired by the smart meter is confidential and private. Proof-of-Location is used in energy trading to ensure that right nodes are used for the automated transactions. It includes activities like tracking apps, location-based access control systems, location-based services, and cognitive radio networks. The blockchain is a multipurpose tool that handles data between different participants, calculates consumers' load baseline that enforces the load reduction, and eventually pays the customers according to the contribution [10].

To achieve secure, automatic, and fair energy transmission, trading is done by blockchain technology. In P2P energy trading, blockchain confirms the payment of energy transmission by smart contract, as shown in Fig. 4 [18]. Smart contracts store the transaction information. They are digitalized forms of standard contracts, which verify and implemented with the minimum human intervention [28]. Smart contracts are executed at every node automatically and independently [24]. Transaction settlement and energy tradeoff are done by smart contracts [29].

IV. Challenges

Blockchain enabled smart metering systems face challenges like poor interoperability and low throughput issues. It faced problems regarding to policy uncertainty and lack of standardization, which leads to grid unbalancing. It required upgraded infrastructure, verifying, and auditing of the transaction record, and maintaining the stability and reliability of the system [3]. Optimization, enhanced security, and fairness in energy trading are required for efficient maximization, make an intelligent energy system, maintain a record of real time energy demand and supply, and preserve the users' privacy details [18], [30]. The blockchain enabled smart meter challenges, solutions, and outcomes are given in TABLE II [31]-[33].

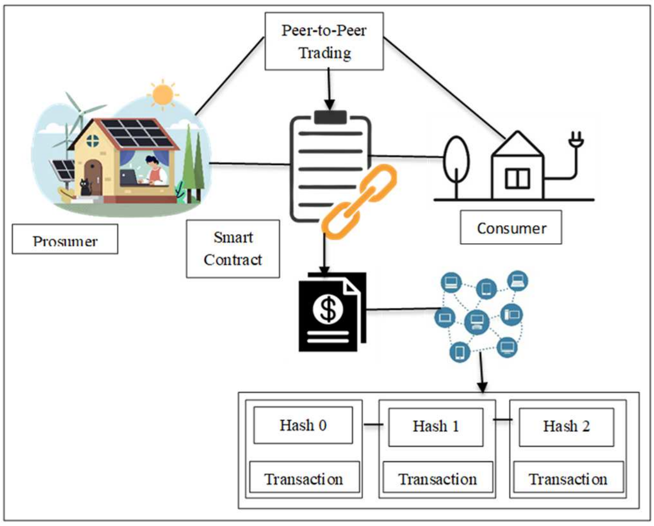

Fig. 4 P2P Energy Trading Using Blockchain

TABLE II: CHALLENGES OF BLOCKCHAIN ENABLED SMART METER, ITS SOLUTION, AND OUTCOMES

Challenges	**Solutions**	**Outcomes**
Privacy & security enhancement	Vulnerable scan & programming correctness for security in smart contract operations	Privacy & secured data sharing
Complexity	Mining of data using data mining techniques like state of art & exploring the features from the perspective of network operators and users	Efficient data mining & effective mobile data management
Network visualization	Software defined networking & large data are integrated with immutable blockchain & faster 5G	Secured data transactions & faster query processing
Blockchain standardization	High level functional architecture for distributed ledger technology & blockchain	Standards for different functionality in the blockchain

V. OPPORTUNITIES

The data generated by the smart meters can have multiple features, such as real time monitoring of energy consumption, energy production, and forecasting [26]. Blockchain based energy systems promise transparency, competition, flexibility, security, and ideal electricity trading in the distribution level energy market. It eliminates transaction fees, handles many participants, avoids monopolies, and allows all participants to participate and bid in the market. There is flexibility to check instant energy prices, incentives, and penalties, making a blockchain system better than any other existing system [27]. Due to blockchain, the companies buy or sell renewable certificates immediately, which now takes weeks or even months. TABLE III gives various opportunities in different sectors [31]-[34].

In India, Blockchain enabled smart metering systems are deployed. There are various places like Delhi, and Uttar Pradesh, which are working on blockchain technology for P2P energy trading and renewable energy certificate. In Delhi, BSES and Tata Power-DDL are working on P2P energy trading pilot project. There are collaboration of Tata Power-DDL and the Australian company's power ledger with India Smart Grid Forum. This project also enables to develop an integrated ecosystem that includes grid connected distributed energy resources, EV charging stations, and battery storage systems. Uttar Pradesh Power Corporation, Uttar Pradesh New and Renewable Energy Development Agency, and Madhyanchal Vidyut Vitran Nigam Limited also have a blockchain based pilot project involving the solar rooftop generated energy systems installed in Lucknow [35].

TABLE III: BLOCKCHAIN ENABLED SMART METER OPPORTUNITIES

Application	**Description**	**Benefits**	**Future Scope**
Smart city	Hash consensus algorithm, blockchain, & asymmetric encryption are used	Decentralized, auditable, secure environment, & tamper-free transactions	Implementation of blockchain for crowd sensing, maintaining accountability & privacy balance
Smart grid	Distributed consensus algorithms & blockchain implementation	Decentralized energy generation & P2P energy trading	Achieve market penetration & commercial feasibility
Smart transportation	Smart contract, fast payment, track, & trace, supply chain finance using blockchain	Decentralization, authentication of data provides an understanding of shipping, transportation, logistics	Varied successful applications considering transportation engineering still not predominant

VI. CONCLUSION

This paper represents the significant features of smart meters and the need for blockchain technology in smart metering systems. It includes a glimpse of blockchain enabled smart meter uses across India. The features of the blockchain are to attract industries and academia both. It eliminates the dependency on a single trusted authority. This scheme supports mutual authentication for secure systems, and confidentiality is a major concern. The identity of the smart meter has not been revealed. After applying blockchain technology to smart metering systems decreases vulnerability, and smart meters are protected from cyber-attacks. In this paper, we mainly focused on various concepts of smart meter data security, privacy, blockchain, and energy trading, challenges, and opportunities of the smart metering system in the blockchain. In the future, the computational complexity of the blockchain system needs to be reduced during P2P energy transactions.

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