Blockchain and Machine Learning for Future Smart Grids

Subjects: Others
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A wide range of solutions, beyond the classical one of building more lines, cables and transformers, have been proposed to modernize the power grid with new technologies, enabling a more smart automatic networked system. These solutions, typically using new technology, go by the name “smart grids” (SG) or “smart-grid technology”. Blockchain technology (BC) is a viable solution to overcome the issues of centralized system. BC is an immutable, distributed and P2P network that provides security, privacy and trust among peers using cryptographic techniques. Machine learning (ML) techniques can be exploited to develop energy prediction algorithms and the proper scheduling of energy usage. A large amount of the energy consumption data of several users is generated from smart meters that also contain users’ private/confidential information as well as sensitive information of utility providers. This high volume of data increases the complexity of data analysis.

blockchain machine learning smart grids energy trading electric vehicles

1. Introduction

1.1. Smart Grids

Traditionally, the term grid is referred to an electrical system that supports the generation, transmission, distribution and trading of electricity. **Figure 1** shows an example of a traditional power grid. A traditional grid transports the electricity generated by large power plants to the electricity consumers. In the distribution network, the energy flow is only in one direction. However, there is a need to replace the electricity from fossil fuel (coal and gas mainly) and manage the increased electrification (EVs, but also in certain industrial processes) that results in higher consumption. Hence, alternative energy sources are required, i.e., RES. Traditional grids have only limited capability to incorporate these sources.

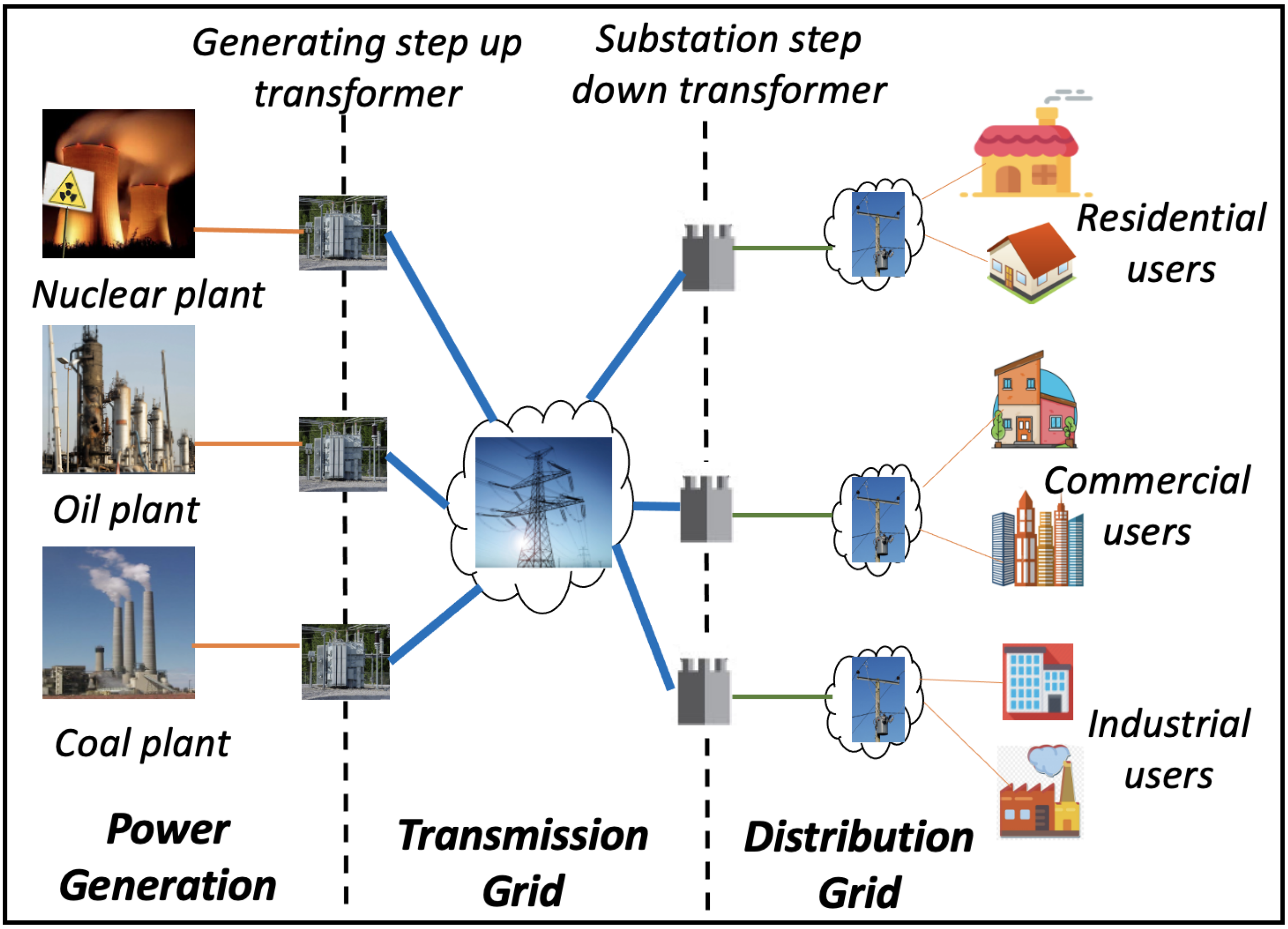

Figure 1. Traditional grid—example.

The smart grid utilizes information and communication technologies (ICTs) to revolutionize the traditional electric power system [1]. The term “smart grid” mainly refers to an improved or efficient power grid that allows the two-way flow of information and electricity. It can be considered the next generation of the power distribution system. Most of the governments and energy companies are performing extensive research on SG applications. The National Institute of Standards and Technology (NIST) [2] USA defines SG as “*A modernized grid that enables bidirectional flow of energy and uses two-way communication and control capabilities that will lead to an array of new functionalities and applications*”. Authors in [3] define SG as “*an electric system that uses information, two-way, cyber-secure communication technologies, and computational intelligence in an integrated fashion across the entire spectrum of the energy system from the generation to the end points of consumption of the electricity*”. SG enables more efficient integration of RESs, such as solar and wind. It employs digital technology that allows communication between devices, whereas a mechanical device is electrically operated in the traditional power grid, which does not allow communication between devices and self regulation. The power distribution from multiple plants and substations is possible in SGs, which aids in the overall load balance, avoids peak time strains and minimizes the chance of power outages. Multiple sensors present throughout the line help to detect the exact location if a problem occurs and reroute power to where it is required, thereby limiting power interruptions. With these sensors and smart infrastructure, electrical companies can control and monitor power distribution and consumption effectively. Sensors can even detect issues on the transmission line and perform troubleshooting without external intervention.

1.2. Blockchain Technology

Blockchain (BC) is a digital, decentralized (distributed) ledger that records all transactions occurring across a P2P network. BC concept was first introduced by Satoshi Nakomoto in a white paper titled “Bitcoin: A peer to peer electronic cash system” [4], but no clear evidence about the author’s identity is available. This is the backbone of bitcoin cryptocurrency, and later more studies were performed to understand the underlying technology of the bitcoin system, i.e, BC technology. It was originally proposed to tackle double-spending problems in financial transactions. Later, the technology won a reputation for its two main critical factors: (1) data immutability; and (2) data indestructibility. In a simple definition, it is an interlinked and expanding chain of blocks which securely records data. Each block is connected to the previous block using secure hashing algorithms by generating a cryptographic hash value for each block. Altering a transaction in BC retroactively requires altering not only the current block hash, but also the cryptographic hash of all the blocks down the chain. The major techniques behind BC is the principle of hashing and consensus algorithms, which ensure security. A new block can be added only if consensus is achieved among the nodes. A distributed system such as BC holds benefits over centralized architectures, as it provides the same verified information to all network members [5]. Ethereum is an open-source BC platform with a Turing-complete scripting language to include smart contract functionality [6]. Ether is the second largest cryptocurrency after bitcoin, and it is among the most actively used BC platforms [7]. A smart contract is a computer script that can be deployed in BC and record conditions or events. When conditions are met or events are reached, the contract will be automatically triggered and executed, which avoids centralized control [8]. Solidity, a high-level object-oriented programming language, is the primary language for writing these contracts [9]. Hyperledger is an open-source BC platform that uses permissioned BC networks, developed by the Linux foundation in December 2015 [10]. It can be used to develop various BC-based systems and applications for industrial use. However, it does not support cryptocurrencies, such as bitcoin and ethereum.

1.3. Machine Learning

Machine learning will give computers the ability to learn without being explicitly programmed. A better definition for ML was given by Tom M. Mitchell as “a computer program is said to learn from experience E with respect to some class of tasks T and some performance measure P, if its performance on T, as measured by P, improves with experience E” [11]. More clearly, as computers/models are exposed to a set of new data, they will adapt independently and learn from previous patterns to interpret available data and identify hidden patterns. ML adopts techniques from diverse set of disciplines that include philosophy, probability, information theory, statistics, control theory, artificial intelligence and so on [12]. ML algorithms are being used in various applications domains, such as financial services, marketing and sales, government, healthcare, transportation, and so on.

ML techniques can be generally classified into four categories: (1) supervised learning; (2) unsupervised learning; (3) semi-supervised learning; and (4) reinforcement learning. **Figure 2** classifies different ML techniques.

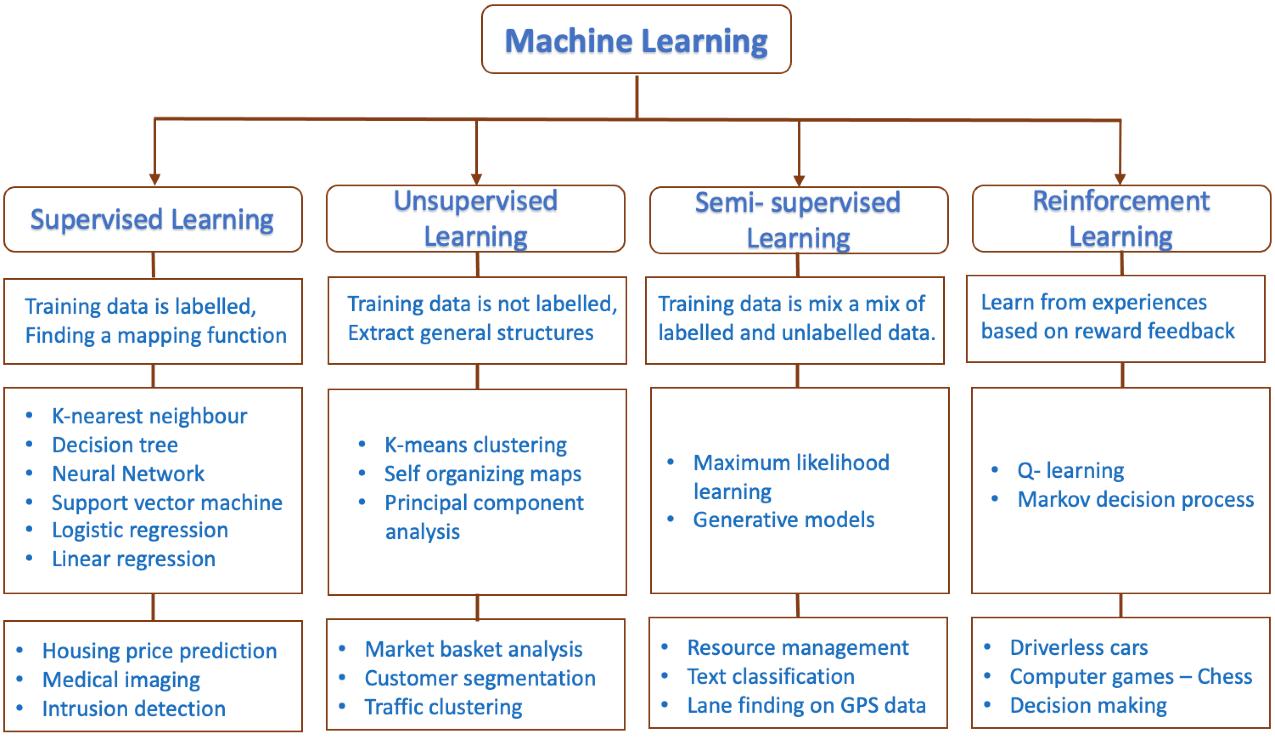

Figure 2. Machine learning algorithms—overview.

ML techniques are mainly categorized into four categories and are widely used in various fields. In the energy sector, ML techniques can be used to predict energy user behavior based on usage patterns, and analyze the big data generated from smart meters, energy forecasting, power quality measurement and DRM. However, the choices of a suitable algorithm, datasets and processing techniques have to be made effectively.

2. Blockchain in Smart Grids

The use of BC technology in the energy sector is a key research topic nowadays. As the energy industry is undergoing tremendous transformations with the adoption of ICT, it has become a prominent research area. Intelligent grid implementation with minimal power loss, high power quality, reliability and security are the main goals to be attained.

The distributed architecture of SG is depicted in **Figure 3**. However, maintaining all these distributed functionalities by a single centralized server is complex and highly vulnerable [13]. The ultimate aim of all the transformations in the grid is to reform the existing energy industry by bringing producers and consumers closer to each other using distributed generation and resources. In centralized systems, all the users, energy operators and market system interactions are dependent on central entities. These intermediaries can monitor, control and support all activities within the elements in the grid [14]. Additionally, the long-distance transmission network is opted to deliver energy to end users through distribution stations. The increase in the number of elements associated with the grid raises some concerns [15], which include scalability, reliability, availability, communication overhead and so on. All of these issues point toward the need for a decentralized structure for energy grids to create a more dynamic and flexible grid structure [16].

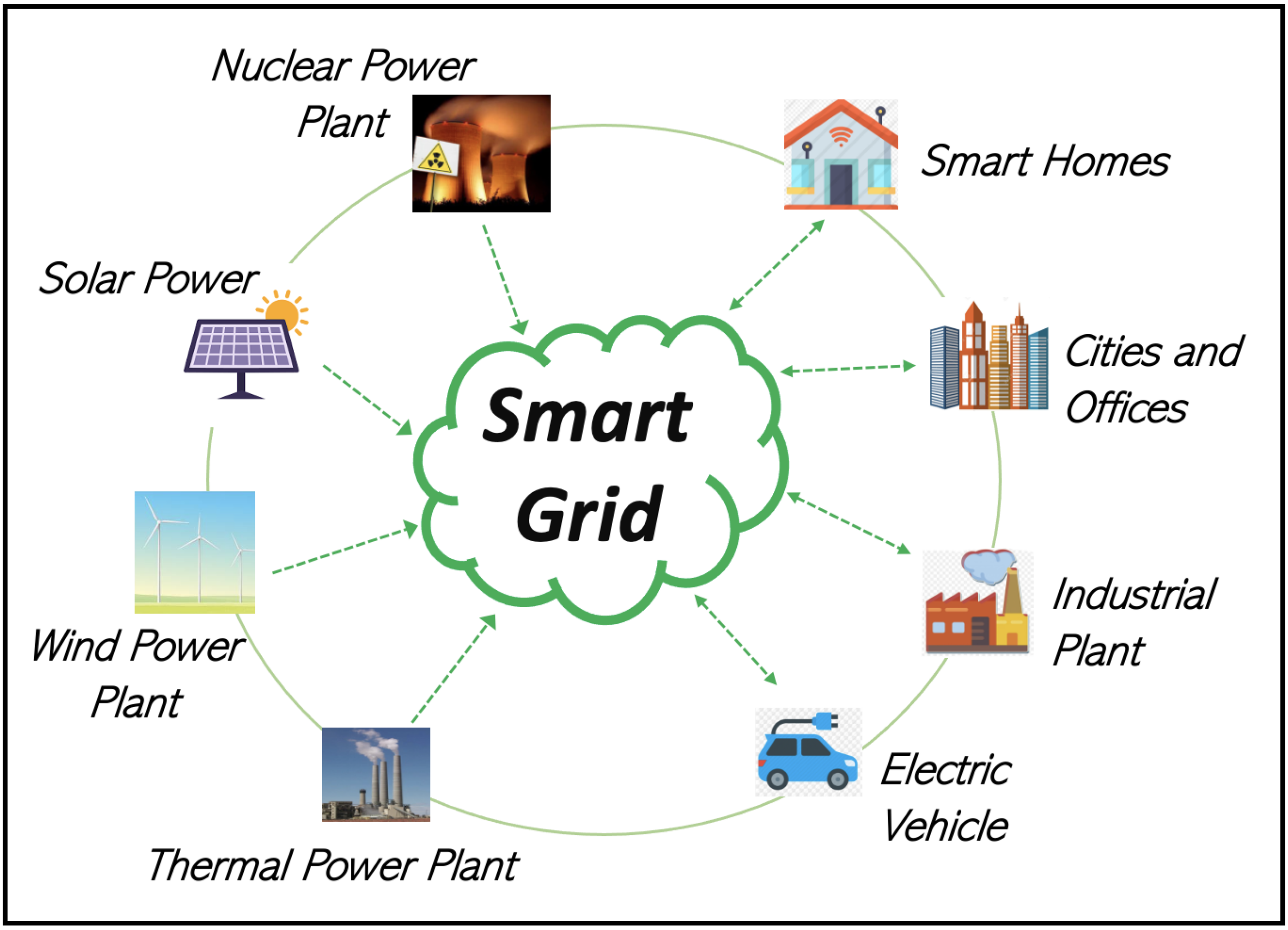

Figure 3. Smart grid—general example.

Security, energy management, EV charging and energy trading are also some of the areas to be transformed and implemented effectively. As users are becoming prosumers through distributed generation, they can trade electrical energy to other grid users. Traditional methods fail to provide a secure and flexible energy trading platform [17] where users can trust each other. Due to privacy and security concerns, most of the users show less interest in participating in energy trading. Hence, a decentralized platform which can create a trust environment for secure energy trading is required. Indeed, the penetration of EVs also has effects, as energy trading between EVs can also be done [18].

All these issues, mainly, the need for decentralization, security and in building the trust platform for trading without third party intervention, point toward the use of emerging BC technology [19]. Applying BC technology in the energy sector has many potential benefits and can avoid most of the bottlenecks in the development of smart grid. Many studies and industry experts believe that BC adoption will eventually help for a smooth shift toward smart grid [13][14][19][20][21]. **Figure 4** represents a model for blockchain-enabled future smart grid.

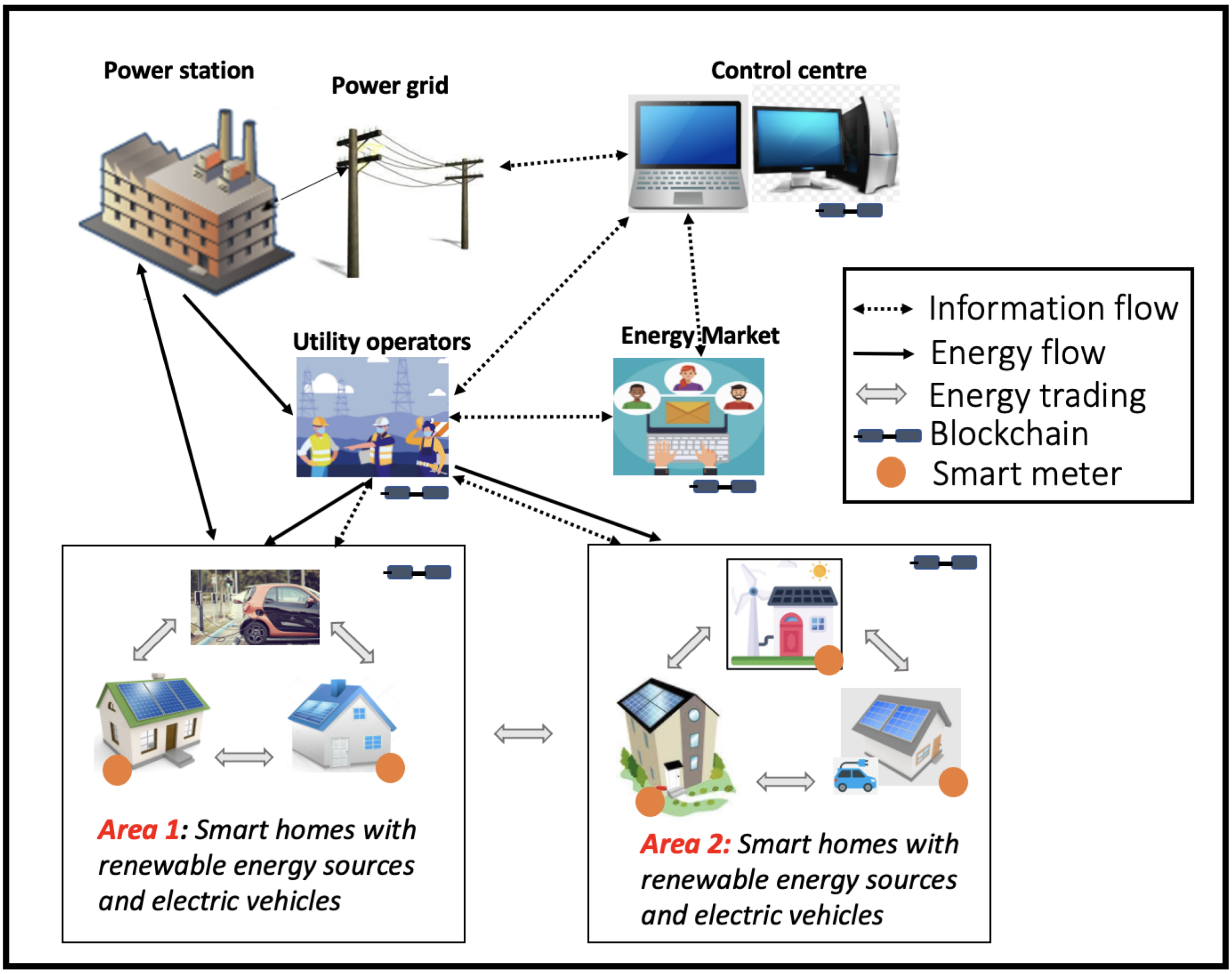

Figure 4. Blockchain-enabled future smart grid.

The main motivation of applying BC technology is to achieve an increased level of security [22]. Since BC uses cryptographic techniques and a ledger is shared among all peer nodes, data alteration is not possible unless the majority of the nodes become malicious. As all the network nodes can verify the transactions and records, it adds transparency to the system. Due to secure hashing algorithms, any malicious activity or faults in the communication network are easily identifiable and recovered easily, which makes the system resilient to attacks. Above all, the most important benefit comes from the secure scripting using smart contracts, which can automate the transactions by automatically executing them when certain conditions are met. Thus, with all these critical features and cryptographic techniques, BC adoption promises to be a suitable alternative to traditional centralized systems with increased security, resilience, privacy and trust [23].

2.1. Energy Trading

Blockchain plays a very significant role in energy-trading applications. BC technology is most widely used in decentralized energy-trading application compared to all others [24]. In **Figure 5** shows a model of energy trading using BC technology. The main reasons for BC adoption in energy trading are transformation from centralized to distributed resources, the need for a secure P2P trading platform among prosumers avoiding third parties, building trust and privacy in the trading platform and managing the needs of all grid users.

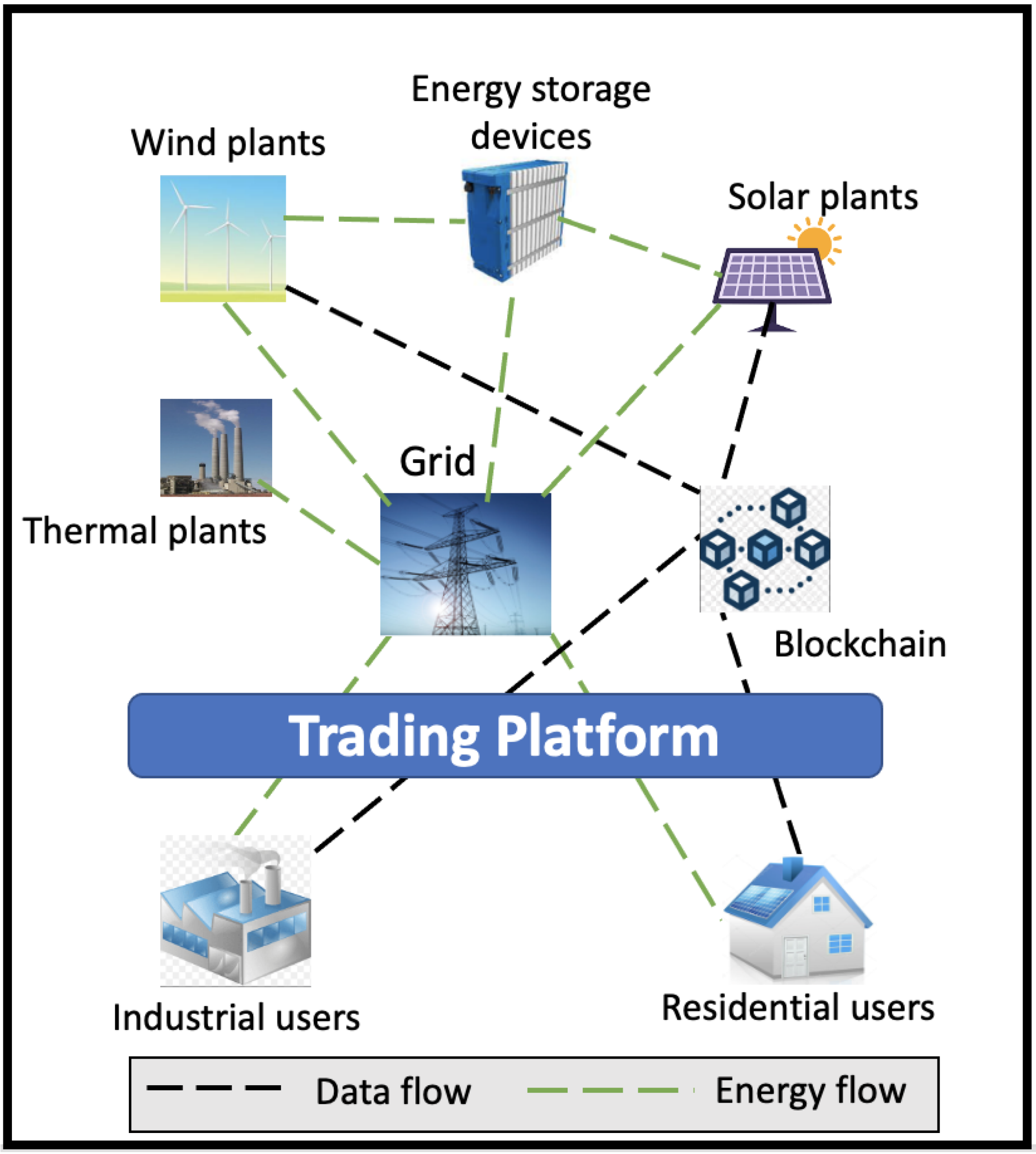

Figure 5. Model of energy trading using blockchain.

2.2. Electric Vehicles

EVs play a significant role in the smart grid infrastructure and they also solve some of the environmental problems by facilitating green travel. However, EV users are facing challenge in charging, as the number of EVs are increasing while the number of available charging stations are decreased. Additionally, short communication ranges, the need for frequent communications and mobility of EVs add new security and privacy concerns [25]. On the other hand, the high penetration of EVs and less-coordinated charging schedules might lead to overloading in the grid. Hence, there in an open challenge to integrate all these EVs in the grid, schedule the charging operations effectively and develop a transparent and secure charging system. Many researchers adopt decentralized BC technology to solve these issues and enhance the use of EVs and its charging management [18][26][27][28][29][30][31][32].

2.3. Demand Response Management

Several research works explore different techniques to develop an innovative DRM system with the adoption of BC technology. The main idea of most of the works was to develop a secure trading platform for distributed prosumers and EVs. Smart contracts which can execute upon reaching desired conditions gained great acceptance in the DR application [33][34][35][36][37][38][39][40]. Some of the works which aims to develop better DR prototypes are listed in **Table 1**.

Table 1. Summary of existing works related to demand response management using blockchain.

Ref	Major Contribution	Technologies Used
[27]	Proposes an EV charging scheme in a BC-enabled SG system which minimizes power fluctuation level in grids and charging cost for EV users (AdBev scheme)	Ethereum, smart contracts
[33]	Investigate use of BC mechanism in demand management by setting up decentralized P2P energy flexible marketplace	Smart contracts
[34]	Design a BC based secure energy trading framework (SETS), having security and privacy preservation to manage demand response management (DRM)	Ethereum, smart contracts, Etcoins
[35]	Explains an algorithm for secure DRM in SGs using BC that helps to take efficient energy trading decisions for managing overall grid load	Energy coins, PoW
[36]	Proposes a secure model for energy trading using BC, contract based incentive mechanism for load balancing and route optimization algorithm to reduce EV traveling time.	Consortium BC, Proof of Work based on Reputation (PoWR), shortest route algorithm
[37]	Proposes a decentralized cooperative DR framework to manage the daily energy exchanges within a community of Smart Buildings and allows participants to decide on day-ahead community power profile, subsequently ensures the forecast tracking during the next day.	Ethereum, smart contracts
[38]	Proposes an energy scheduling scheme among multiple microgrids, EV energy scheduling integrated with microgrid operation and introduces a contribution index to prosumers and whole microgrids for prioritizing in auction.	Smart contracts

References

Ref	Major Contribution	Technologies Used
[39]	Introduces a BC-based transactive energy(TE) auction model with incorporated DR techniques for increasing social welfare.	Smart contracts
[40]	Addresses the sustainable microgrid design problem by leveraging BC technology to provide the real time-based demand response programs.	Smart contracts
[41]	Proposes an optimal power flow based DRM system without any central authority	Smart contracts

2.4. Security and Privacy

Smart meters placed at each home in a smart grid provide real-time information about electricity consumption and pricing. This information may contain aspects about users which are private and thus require mechanisms to preserve privacy. If a malicious attacker gains access to this data, they can track the energy usage behavior of users based on their consumption profile. The major concern for every user or entity in the SG environment is privacy, and the associated security of such information exchange [22]. Most of the works aim to provide security and privacy in smart grid operations using BC technology. Similarly, security of power information system is also an important area of research. SG incorporates several communications for proper functioning and power delivery, and this information has to be stored securely. If the system is hacked, it may impact the grid and create unpredictable effects in the grid, leading grid operators toward making wrong energy decisions, eventually resulting in interruptions or even large-scale blackouts. Providing security for all parts of the SG is critical. The use of BC alone does not directly guarantee security and privacy; however, adding advanced cryptographic mechanisms such as multi-signatures, elliptic curve cryptography, etc., are also needed.

3. Machine Learning in Smart Grids

3.1. Attack Detection and Security

Ref. [42] addresses the problem of false data injection in smart grid and ML-based techniques to detect such attacks. Information exchanges in SG are mainly unidirectional, for example, information to control centers based on measurements. These data should be clearly monitored for studying malicious behaviors in the SG. Their work mainly uses two ML techniques to detect attacks in SG (supervised and unsupervised techniques) and classify normal data and tampered data. Ref. [43] uses clustering methods to find representative periods for optimizing energy systems.

3.2. Data Analysis

In [44], a comprehensive study on the application of big data and ML and the associated security concerns in the electricity grid is presented. The massive data generated from the grid, termed ‘Big Data’, require proper optimization from generation to distribution side and have to be processed/analyzed by implementing effective security solutions. Two major concerns regarding any data generated in SGs are processing the gathered data by

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satisfying the time limits and removing the involved security concerns [44]. ML techniques can be applied to predict the usage patterns and energy needs of users in SG. Solar power plants and other RESs are affected greatly by seasonal changes. Thus, a system that can predict, in advance, solar energy information is required to minimize the operational costs caused.

3.3. Demand Response Management

Ref. [45] studies demand response algorithm implementation for SG residential buildings using ML models. They combine the optimization technique and ML models to find the optimal strategy for DRM and use metered data to train and test the algorithm. Two demand response algorithms—rule-based and predictive-based (ML-based)—were deployed and evaluated using a common demand price scheme. Ref. [46] compares two ANN-based load forecasting techniques: echo state network (ESN) and feed forward neural networks (FFNN) for demand response programs in SGs. The novelty of their method is that they compare two ANN techniques over a complete and heterogeneous data set which are pre-processed with adaptive clustering techniques for achieving optimized forecasting performance. Their work can help power system planners for forecasting user-based profiles and implement DR programs.

4. Integration of Blockchain and Machine Learning for Smart Grids

Combining BC and ML for various applications is increasing. The learning capabilities of machine learning can be applied with blockchain to make the chain smarter [47]. Additionally, the computational power for ML models can minimize the time taken for the nonce calculation. On the other hand, using the decentralized data architecture of blockchain, better ML models can be built. The main benefits of combining BC and ML are (a) security, (b) improving energy consumption, (c) improving the smart contracts, (d) data trading and more. BC is a continuously growing data ledger, whereas ML requires large volumes of data. Both techniques complement each other and have high potential when combined for different applications.

With the decentralized and immutable structure, BC builds a trust environment without third parties for any transactions occurring. ML-based solutions mainly help in demand management using prediction techniques and help in handling large amount of data from smart meters [48]. Additionally, optimization techniques can be used for scheduling the energy usage of users. Applying BC into ML systems helps such systems to use information collected by BCs to clear problems quickly, and applying ML techniques to BC adds powerful intelligence to BC systems for data processing and other intensive applications [11]. The storing of large-scale data in a secure and tamper-proof manner by BC-based systems ensures the confidentiality and auditability of the collaborative data training process and trained model using cryptographic techniques. Additionally, it enables decentralization that ensures access control without central authorities. Smart contracts and DApps allow to model interactions between entities in the decentralized ML application. In the same way, adding ML helps the BC system to achieve energy efficiency, scalability, security and intelligent smart contracts. As ML can predict and speedily calculate data, it provides a feasible way for miners in selecting important transactions. Using predictive analysis can ensure energy

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and resource requirements to [illegible] and improve overall efficiency. Hence, considering the future SG scenario, both BC and ML can together solve the issues regarding energy trading, EV charging and scheduling, load prediction, DRM, security and privacy concerns. Table 2 summarizes the existing works that combine BC, ML and SGs.

Table 2. Summary of existing works related to BC, ML and SGs.

Ref	Major Contribution	Technical Resources
[49]	Evaluate the development of a decentralized EV charging infrastructure using BC, AI and SGs	-
[50]	Proposes a decentralized electricity trading framework (DETF) for connected EVs.	Hyperledger, smart contracts, predictive bidding
[51]	Proposes DeepCoin, a BC and DL based framework to protect SGs from cyber attacks.	Recurrent neural networks, Hyperledger, PBFT
[52]	Explains P2P trading system for sustainable power supply in SGs using BC and ML	Hyperledger, smart contract, PBFT, Predictive model using LSTM
[53]	Explains an intelligent EV charging system for new energy companies using consortium BC	Smart contracts, Limited Neighborhood Search with Memory (LNSM) algorithm
[54]	Proposes an energy trading approach using machine learning and blockchain technology	Smart contracts K-nearest neighbor

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