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Review

IoT-Based Decentralized Energy Systems

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Abstract: In traditional energy production at large-scale, conventional methods are being used, including fossil fuels. This in turn leads to greenhouse gas emissions (e.g., carbon dioxide or CO_2) that cause environmental concerns, but also those traditional methods rely on traditional distribution systems, which are burdened with high transmission losses. This paper focuses on a new concept in the energy sector that undergoes transformation from a traditional centralized system to a decentralized one. In reaching sustainability goals, such as net-zero emissions, the energy sector is incorporating renewable energy sources into the energy system. This requires transformation that combines big conventional energy producers with multiple small- and large-scale energy producers (rooftop photovoltaic panels, wind farms and solar plants) in one system. This enormous transformation is a difficult task, but with recent advancements in information and communication technologies, digitalization, the Industry 4.0 paradigm and Internet of Things technology, it is feasible to achieve. This paper provides a review based on keyword bibliometric analysis, and although it cannot be considered exhaustive or conclusive, it provides a picture of the current international research.

Keywords: blockchain; Internet of Things (IoT); fog computing; smart grid (SG); Internet of Energy (IoE); electric vehicles (EV); renewable energy sources (RES); decentralized energy

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1. Introduction

The world's growing population and growing number of electric devices have led to an increase in electricity consumption [1]. Moreover, modern society and economics depend on electricity. Technology innovations that are used in our everyday life are electricity-driven [2]. There is an urgent need to balance the supply–demand of electricity [3,4], especially in the view of sustainability and energy security. The energy sector, which is facing the global trend toward a net-zero emission target, needs to modify energy production behaviors. However, this is not an easy task, and to achieve this, the use of renewable energy sources (RESs) and new power sources are required [3]. Traditional power plants, however, which provide stable electricity supply via the grid, bring inevitable environmental effects [5]. The energy sector is forced to move, nowadays, due to different environmental regulations, towards clean energy. The growing interest in RESs incorporated into an energy distribution system can help in securing the energy supply especially in areas with high electricity demand (e.g., smart cities, smart factories, smart hospitals and smart transport). In addition, RESs compared to traditional fossil fuel energy sources have lower carbon emissions (there are different carbon allowances that undergo trading) [6].

Renewable energy technologies, which are constantly developing and improving, have shifted the role of traditional consumers to prosumers [7]. For example, someone having photovoltaic panels (PVs) can sell their excess energy to the grid provider or other prosumers such as their neighbors [2]. As RESs are cheaper and faster to build than coal or gas generators, there is an increasing number of privately owned generators that join the energy market and are a foundation for a distributed energy system [8]. To sum up, distributed generation is the production of electricity from different small sources [5]. Those small-scale RESs led to the emergence of the idea of a microgrid (MG). On the other hand, there are also large-scale plants such as wind farms or solar parks [9]. In traditional energy production at large-scale, conventional methods are being used, including fossil fuels. This in turn leads to greenhouse gas emissions (e.g., carbon dioxide or CO_2) that cause environmental concerns, but also those traditional methods rely on traditional distribution systems, which are burdened with high transmission losses [7,10].

With more and more things (sensors and actuators) connected to the internet, a new paradigm of the Internet of Things (IoT) has emerged. It is a network of interconnected things and their elements that are able to exchange data with one another over the internet. These include various home appliances, smartphones, smart bands, smartwatches, weather stations and many more, to give an example. IoT is at the forefront of emerging technologies due to the ubiquitous use of sensor-embedded devices [3,11]. IoT enables real-time sensing, actuating, communication and processing in many cases without human intervention. Due to its multiple possibilities, it has been utilized so far in peer-to-peer (P2P) networks, smart homes, smart hospitals, vehicle-to-vehicle (V2V) communication, wearables and smart energy grids [2,11,12]. In present times, the real-time monitoring of an electrical network such as smart grid (SG) is required and can be achieved by means of IoT as it allows for grid automation [3,13].

The energy sector, which is undergoing a transformation from a centralized to a decentralized system, will be the biggest consumer of IoT edge devices, with 1.17 billion in 2019 and 1.37 billion devices in 2020 (26% Greater China, 12% Western Europe and 8% North America) [14]. According to [13], the growth of the smart home market is expected to reach USD 53.45 billion by 2022. The energy sector is integrating operational and information technologies in order to reach the growing demand for energy and legal requirements (a zero emissions target) [15]. Due to the COVID-19 pandemic, the global energy demand has decreased by 6% in 2020 compared to 2019 [16]. However, it will increase up to 30% by 2040 compared to 2017 [17]. Moreover, in 2019, the global renewable capacity reached 2537 GW. It is estimated that in 2050 the global energy demand will be 8% lower than today but will be provided to 2 billion more people [16]. In addition, in 2020 in Finland, the share of RESs has increased to almost 40% [18]. This requires significant investment in order to achieve those sustainability goals. It is estimated that the European Union alone, to transform to a sustainable and reliable energy system, needs to invest a minimum of 200 billion euro and the United States USD 2 trillion by 2030 [9]. Guaranteeing stable energy distribution, especially during peak hours with an increasing number of electricity-driven devices, creates a great challenge for the energy sector. Obtaining this is crucial, as power outages in the US market cost USD 150 billion annually, with equipment failures being responsible for around one third of them [11].

The paper provides a review based on keyword bibliometric analysis and although it cannot be considered exhaustive or conclusive it provides a picture of the current international research. The rest of the paper is formed as follows: Section 2 describes the implementation of the Internet of Things in the energy sector providing opportunities and the limitations it brings. Section 3 contains bibliometric analysis methodology and obtained data analysis. Section 3 takes up the idea of a smart energy grid system. In Section 5, the concept of a smart grid (SG) is presented. Section 6 focuses on smart grid (SG) challenges. In addition, Sections 7 and 8 present the Internet of Energy (IoE) concept and the implementation of blockchain (BC) technology in decentralized energy sector.

2. Internet of Things in the Energy Sector

The Internet of Things (IoT) delivers many novel solutions that can be implemented in the energy sector. IoT is based on smart technologies such as sensors, actuators and intelligent systems that can be integrated and enable digitalization industries (including the energy sector), providing a novel paradigm in business operations. The processing of enormous amount of sensor-generated data are supported by development of information systems such as cloud computing technologies that provide decentralized sharing and access to information from different geographical locations. The enormous amount of data generated from IoT allows efficient analysis and supports decision making and a quick response to system failures [19–21]. It plays a significant role not only in a digitalized and connected society, but also in industry, healthcare, transportation, etc., and the economy as a whole [22].

It can support the transformation from a conventional energy grid to a modernized smart grid (SG) system. As IoT enables a two-way communication of sensors and devices, it can improve the operation and control in a traditional grid [3,11,13]. IoT, by providing the structure and protocols required for sensing, communication and processing, paves the way for smart energy system with efficient grid automation and control. When sensors and smart metering are implemented in a power grid it becomes a smart grid (SG) with the ability to overcome most electricity industry challenges, such as power generation and distribution. In addition, IoT in a smart grid (SG) allows for the real-time monitoring of power flow and can support decision making in relation to power sources and demand. This in turn can help in balancing supply–demand and elevating energy efficiency. Furthermore, IoT on the end-user side can support the real-time monitoring of energy consumption and help to regulate power uses more effectively. This can be achieved through smart home technology enabling remote (web or mobile application) control of IoT connected devices. This allows for a better control and regulation of smart systems in homes and buildings, thereby helping in energy waste reduction [3,23,24].

The biggest challenges of a conventional power grid system are reliability and power quality that can be overcome with the implementation of IoT. The transformation from a conventional grid to a smart grid (SG) system can be achieved with the utilization of advanced metering infrastructure (AMI), together with smart metering technologies (SM) [5,25–29]. AMI can gather information from the grid such as energy consumption, voltage, current readings, etc., [30]. The huge amount of data being generated can be efficiently transmitted and processed with IoT technologies and support quick response and decision making for effective energy management. The key benefits of IoT in smart grid (SG) systems include:

- Scalability,
- Heterogeneity,
- Energy efficiency,
- Dynamic nature,
- The detection of cyber-attacks [3].

IoT provides the technology to gather and transfer data from the energy grid in real-time and an infrastructure to efficiently process that huge amount of data through edge computing. IoT computing architecture has been described in previous work [31].

3. Research Method

The paper is based on a literature review method considering PRISMA guidelines. This approach allowed for the identification of different studies related to the one undertaken. It is necessary to mention it cannot be considered exhaustive or conclusive; however, it provides a picture of the current international research. This research focused on the relationship between blockchains, IoT, smart grids (SGs) and energy. As keyword searches are most common in identifying the relevant literature, the author used common Boolean operator AND [32]. The following search scheme was adopted in two major databases:

- Scopus database (TITLE-ABS-KEY (blockchain) AND TITLE-ABS-KEY (iot) AND TITLE-ABS-KEY (smart AND grid) AND TITLE-ABS-KEY (energy)) AND (LIMIT-TO (PUBSTAGE , “final”)) AND (LIMIT-TO (LANGUAGE , “English”));
- Web of Science Blockchain and IoT and Smart Grids and Energy (All fields).

The research was conducted at the turn of August and September 2022. No temporal restriction was chosen. The search was limited to the publication stage and English language. When the research criteria were met, an initial sample of 230 papers (127 in Scopus and 103 in Web of Science) was identified. In the next step, duplicates were excluded as well as papers not connected to the scope of the paper. The sample was further limited to publication with full-text access resulting in 75 publications as the main sample.

The metadata of the papers were exported in comma-separated value (CSV) and .txt formats, which provided necessary information on the papers (title, authors' name, authors' affiliations, abstract, keywords and references).

Data Analysis

Figure 1 shows the publishing trend of publications meeting the selection criteria. There were no publications dating earlier than 2016 (Scopus) and 2017 (Web of Science). Recent years show an increase in the number of publications. As there were no publications found that met the keyword search criteria before 2016, this is considered a recent subject. Although there are many publications with the selected keywords and their different combinations, there are relatively few works covering all of them.

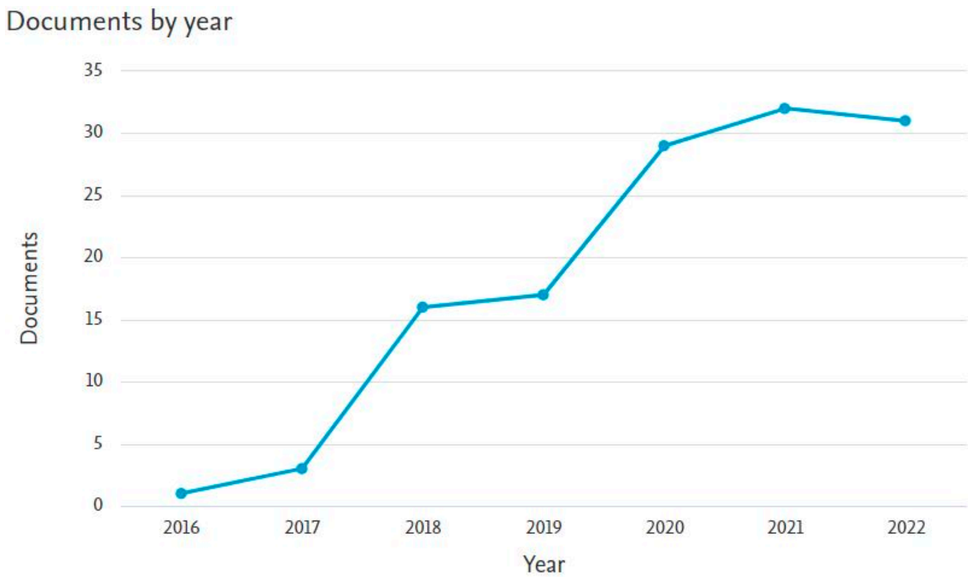

Figure 1. Publishing trend of the sample. Keywords: blockchain, IoT, smart grids and energy.

Figure 2 presents the types of publications retrieved from the databases search. As can be noted, almost half of the published papers are conference papers and over one third are articles.

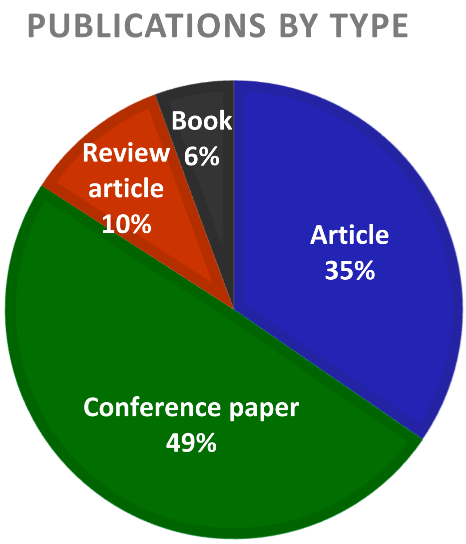

Figure 2. Publications by type. Keywords: blockchain, IoT, smart grids and energy.

The obtained bibliometric data were used for further analysis as it allows for macro-level assessment in the field area [32]. VOSviewer software was used [32–34] to calculate and graphically present the matrix of keyword co-occurrence. It calculates the frequency of two keywords appearing together in one paper and, as a result, a symmetrical co-occurrence matrix based on the word co-occurrence is obtained. Moreover, "the higher frequency of co-occurrence between keywords, the closer research theme is" [34]. In Table 1, keyword clusters based on the VOSviewer co-occurrence analysis are presented.

Table 1. Clusters from bibliometric analysis.

Cluster	Cluster Color	Number of Keywords	Cluster Keywords
1	Red	10	artificial intelligence blockchain cybersecurity electric power transmission networks information management internet of things internet of things (iot) iot smart grid smart power grids
2	Green	7	energy efficiency energy trading energy utilization intelligent buildings peer to peer networks power markets smart city
3	Blue	6	block-chain distributed ledger energy renewable energies renewable energy resources smart contract
4	Yellow	5	data privacy energy resources network security smart contracts

The next step was to make a map of the analyzed co-occurrence matrix to better visualize the relationships between the keywords form the bibliometric analysis, as shown in Figure 3. The color nodes represent keywords, wherein the larger the size of a node, the higher the frequency of a keyword [34]. Nodes are connected using lines showing the connections between keywords. Moreover, the thicker the lines between words, the closer their relationship. It was observed that of the 913 recurring terms, only 28 occurred at least eight times. With the highest frequency of occurrence are such keywords as blockchain, internet of things, smart grid and internet of thing (iot).

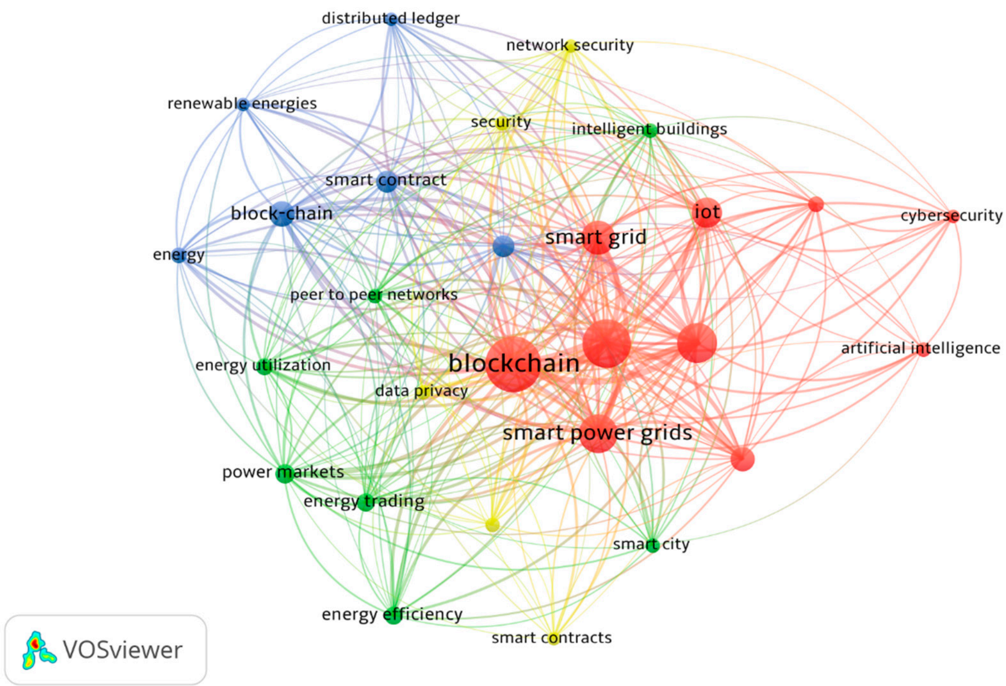

Figure 3. Map of co-occurrence matrix.

4. Smart Energy Grid System

Smart grid (SG) is described as technology-assisted efficient electric grid information that increases its performance through smart energy management. Smart grid (SG) also uses RESs (e.g., solar power, wind energy, geothermal energy, hydro energy, tidal energy and biomass energy) and interacts with energy prosumers and consumers. This energy exchange between prosumers and consumers helps to balance supply–demand of energy and is an emerging vehicle-to-grid technology (V2G) [1,2,5,6,15,23,35–38]. Smart grids (SGs) are therefore decentralized energy systems [39,40]. They are different from conventional grids as they provide a self-managing feature, thereby leading to a more reliable grid [41,42]. The term smart grid (SG) was first used in 2003 by Michael T. Burr [5]. An IF 2000 undersea connection located under the English Channel generates 2000 MW high-voltage direct current (HVDC) and connects the national energy networks of France and the UK [5]. Despite their advantages, they have some shortcomings such as "faults in power generation panels, dust accumulation on electricity-generating panels, conductors galloping and icing". These are associated with renewable energy source that are used in smart grids (SGs) to meet the growing demand for electricity [13,16,43].

It is expected that the global smart meter market will reach USD 10.4 billion in 2022, and it is estimated that compound annual growth rate (CAGR) will be 12% in the period from 2020 to 2027 [13].

Based on IoT computing architecture an IoT-based smart grid (SG) typically consists of three layers:

- Data collection,
- Data communication,
- Data processing [3,12,44].

However, there are works in which other layers are added in order to group different services [12,44,45]. As shown in Figure 4, the data collection layer consists of numerous sensors and actuators collecting different data (e.g., temperature, moisture, noise, energy consumption, water consumption and location) and transporting them to the data communication layer (e.g., switches and routers) [23,46]. At the top of this architecture is the data processing layer (e.g., big data analytics, artificial intelligence and cloud computing) [40].

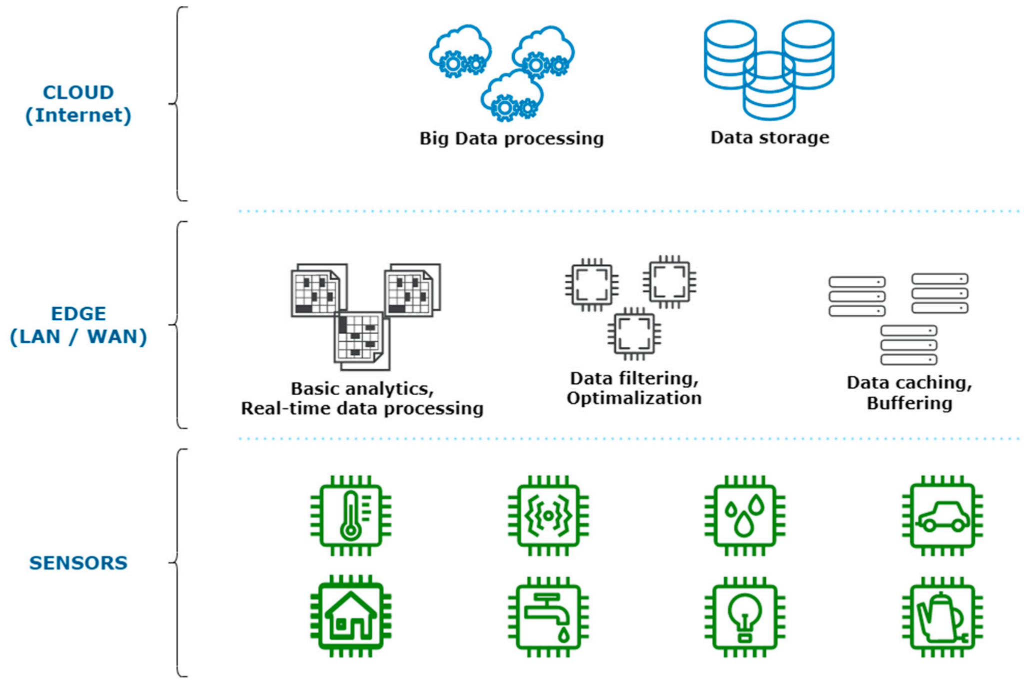

Figure 4. IoT architecture for smart grid.

Sensors are small elements embedded in a device that are responsible for measuring or detecting a change in a condition, such as temperature, light, movement, pressure, magnetism, humidity, particulate matter, etc., and then generating an electronic signal [13,24]. They can be connected in a network able to transmit data to remote locations by means of wireless sensor networks (WSNs) [3,24]. These networks use a message queuing telemetry transport (MQTT) protocol [47]. This protocol is a machine-to-machine (M2M) publish/subscribe messaging protocol for sensor and actuator solutions. Raspberry Pi gateway uses this protocol for communication with the cloud [48]. Another publish/subscribe messaging protocol used in smart grid systems is an open platform communications unified architecture (OPC-UA) developed by the OPC foundation [49,50]. An actuator is an element that can convert the electronic signal into an act, e.g., motion (in automatic doors and automatic lights). Signals produced by sensors can also be transmitted over the network for gathering and processing. These actuators in order to create motion can be categorized, based on the energy source, as pneumatic, hydraulic, thermal and electric ones [3,24].

The data communication layer is responsible for transmitting sensor raw information to a remote utility for further processing and is comprised of gateway devices. This network can be either a local area network (LAN) or a wide area network (WAN). Local area network communicates between sensors/actuators and a local gateway, whereas a WAN transmits data from LAN to the desired location for processing.

4.1. Local Area Network (LAN)

As LAN operates within a local network, it requires specific communication technology. Most common are Bluetooth, Wi-Fi, NFC, UPnP, ZigBee or Ethernet. Bluetooth is a short-range technology that can transmit data between devices over air interface. The 5.2 version has improved features, among others, power efficiency—low-energy (LE) Bluetooth. Wireless Fidelity (Wi-Fi) operates over radio waves and "uses the frequency of 2.4 GHz Ultra High Frequency and 5 GHz Super High Frequency ISM radio band in the domain of 0–250 m at data transmission rate of 54 Mbps". Universal Plug and Play (UPnP) enables the control of small smart home devices or appliances but is not suitable for commercial surroundings. ZigBee is a power efficient, short-range wireless networking technology with the ability to create a wireless personal area network (WPAN) [3,24]. "Ethernet is a group of wired network technologies used in LAN" and wide area networks (WAN). Ethernet is applied in industrial applications (e.g., supervisory and fieldbus networks) [50,51].

4.2. Wide Area Network (WAN)

Wide area network operates over a wider area than LAN and, thus, requires different communication technology. Narrow-band Internet of Things (NB-IoT) uses a subset of long-term evolution (LTE) standard for wireless broadband communication [52]. Another technology is Sigfox—a narrow or ultra-narrow band technology that covers 3–10 km and 30–50 km in urban and rural areas, respectively. A technology with long wireless range is long-range (LoRa) that for IoT purposes uses a low-power wide area networking (LPWAN) protocol in LoRa-WAN. The LoRa-Wan protocol, in combination with LoRa devices, empowers IoT applications [3,24].

4.3. IoT Computing in Smart Grid (SG) Systems

In the processing layer, the closest to the end device are edge and fog computing. In edge computing, an edge device based on locally processed data can make the decision. Fog computing is suitable for resource constraint WSN, as it provides proximity and location awareness, but also hierarchical organization [26]. It acts without extra time required for further analysis in the cloud, as sensor collected data are sent to the fog for processing rather than to cloud servers. On the other hand, cloud computing is an on-demand availability of, e.g., servers, storage, virtualization and applications. It provides on-demand network access to distributed computing resources. The cloud offers multiple users access to data centers located in different geographical locations over the internet. In IoT cloud is used for the aggregation and processing of data coming from sensors and actuators, finally presenting the outcome of analysis to the end user. To achieve this outcome, a massive amount of data are gathered from various sensors and actuators. Approximately, 1 million smart meters in a smart grid (SG) can generate 2920 Tb data with a sampling rate of 4 per hour [26]. The data needs to be efficiently analyzed, but also stored and transferred in a secure manner. Big data analytics (BDA) with machine learning (ML) and artificial intelligence (AI) can analyze and present that sort of data [3,15,53]. Owing to the implementation of those technologies in smart grids (SGs), grid engineers are provided with a tool for more effective energy production management, which leads to outages reduction and allows for less peak-time power control [13].

4.4. SCADA System for Energy Grids

The supervisory control and data acquisition (SCADA) systems are vital in energy systems. SCADA collects data from the energy grid (sensors, cameras and IoT devices); it also supervises automatic procedures in order to control and regulate system parameters. The general SCADA structure consists of sensors and actuators that are controlled and communicated through remote terminal units (RTUs). Human actions, e.g., supervision, can be implemented in the system through human machine interfaces (HMIs) [54]. The SCADA system due to IoT implementation has become even more efficient and complex [54]. The SCADA interface allows system operators to (based on processed data) make decisions and adjust grid parameters. Through IoT real-time monitoring SCADA can quickly detect and communicate faults protecting power lines from potential damage [3,5,13,45]. The SCADA architecture consists of three layers, namely: thing layer, edge layer and cloud layer. Within the thing layer terminal, devices (e.g., sensors, actuators and IoT devices) are interconnected based on efficient communication technologies, such as Wi-Fi, Bluetooth, LTE, NFC or ZigBee. The edge layer is a combination of network devices such as gateways, switches, routers or access points. The SCADA servers in this layer shorten the distance between terminal devices and database, thus, reducing response time. The third layer—the cloud layer—consists of cloud SCADA servers where data are aggregated, analyzed and stored [45].

4.5. Standardization

Data collection from different architecture layers depend on the devices utilized in that layer. As there are many kinds of sensors manufactured by many different entities, in order to make the connection between devices possible, world-wide organizations create standards and protocols. The International Organization for Standardization (ISO) created standards regarding radio-frequency identification (RFID), such as ISO 18047, ISO 15459, ISO 18000 and ISO 11784. In wireless sensor networks (WSN) ISO/IEC 29182, the Institute of Electrical and Electronics Engineers (IEEE) 802.15.4 standards are made. There are also other standards for short-range communication (e.g., Wi-Fi, Bluetooth and UPnP) [3]. Microgrids, however, have different standards such as ISO/IEC 62264 or IEEE 1547 [55].

5. Smart Grid Concept

In a smart grid (SG), all operations and mechanisms are controlled and managed by an algorithm, in other words, it is a typical cyber-physical system. The smart grid (SG) architecture is like the IoT computing architecture in Figure 1. However, there are differences, as shown in Figure 5.

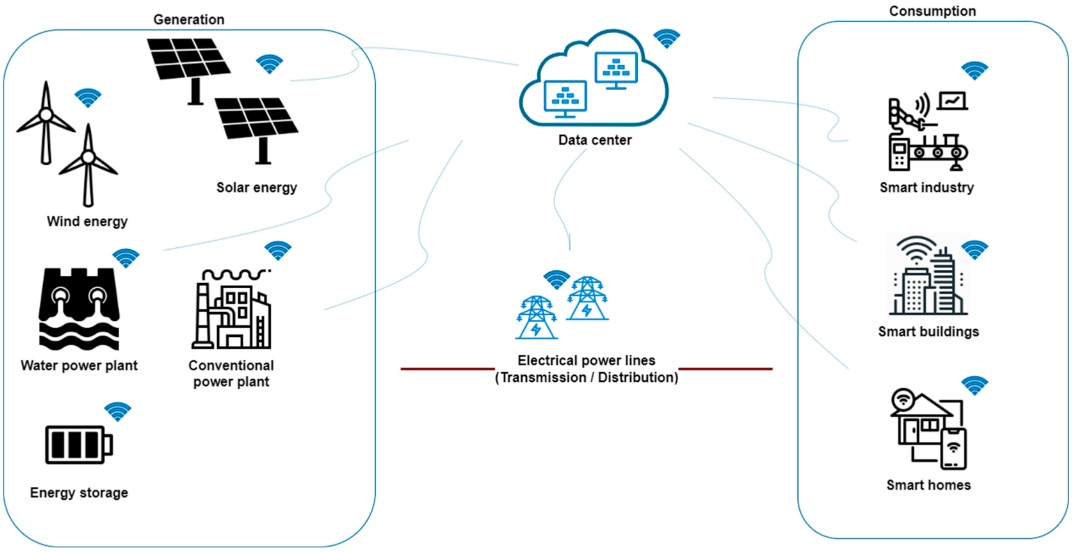

Figure 5. Energy trading architecture in the smart grid.

In a smart grid (SG), power is generated by conventional power plants, large-scale and small-scale RESs, which is then sent to the transmission lines and through distribution lines reaches consumers (individual, commercial and industrial). The entire electricity channel is embedded with sensors interconnected over the internet for real-time data acquisition, processing and for effective energy management as well as reliable and secure power supplies [26,56,57].

Among renewable energy sources is solar energy that can be converted into energy by photovoltaic (PV) panels. A photovoltaic panel is simply an installation of photovoltaic cells placed in a framework called modules. Connected in a series of parallel modules, they create a panel. Thereafter, a number of connected panels make an array. Those solar cells absorb sunlight, and a PV module transforms it directly into direct current (DC) energy [58]. Cells are made of hundreds of different photovoltaic materials, such as polycrystalline silicon or thin-film technology, but their morphologies and efficiencies differ [58,59]. One of the PV materials is solution-processed bulk-heterojunction organic solar cells (OSCs). The morphology of those cells is the main aspect for achieving ultimate photovoltaic performance [60]. These cells use solution-processable organic semiconductors with tunable optoelectronic properties. Utilizing organic solar cells (OSCs), in contrast to crystalline inorganic photovoltaics (PVs), can lead to building-integrated photovoltaics (BIPVs) with see-through power windows [61]. With the application of morphology optimization strategies, it has been reported that OSCs have acquired over 18% power conversion efficiencies (PCEs). Compared to traditional single-junction solar modules with a power efficiency of around 10.7% and tandem solar cells 11.55%, OSCs provide better efficiencies [59]. To obtain best single-junction OSC efficiency, their power conversion efficiency (PCE) must be enhanced. This can be achieved by constructing ternary blends. The research conducted by [60] showed that cutting-edge efficiencies were achieved for co-solvent-processed ternary OSCs using an amorphous polymer acceptor (BN-T: poly[3,9-didodecyl-4,4,10,10-tetraphenyl-4,10-dihydrothieno[3′,2′:3,4][1,2]-azaborolo[1,5-α]thieno [3′,2′:3,4][1,2]azaborolo[1,5-*d*]pyrazine-5,11-diium-4,10-diuide-*co*-2,5-thiophene]). The authors in [61] developed a high-performance see-through power window using semi-transparent organic solar cells (ST-OSCs) showing energy generation and saving functions. The authors used near-infrared (NIR) ternary photoactive blends and introduced a third NIR component into the host binary blend. Furthermore, the calculations of annual carbon dioxide (CO_2) emissions reduction in China and worldwide were made, amounting to 0.13 and 0.67 billion metric tons, respectively. This, in turn, equals to around an 89 kg carbon emission reduction per capita. In another work by [62], a double-skin ventilated transparent photovoltaic window showed reduced energy consumption of air conditioning and good power generation.

This is an economically viable solution for already existing power grids that improves efficiency, connectivity and digitalization [25]. This is only a step forward in today's power systems, because applying IoT technology paves the way for further development in the power sector.

6. Challenges of Smart Grids

As smart grid (SG) systems are based on IoT technology, they are prone to its vulnerabilities. IoT devices, in general, have limited power; many of them are battery powered, which leads to battery development to extend their life [3]. In [26], some examples of smart grid (SG) challenges are described, such as the real-time control of the monitoring of grid operations, scalable and distributed smart grid (SG) architecture, reliable power supply, security and privacy preserving and effective RES and V2G integration. Every internet-enabled system encounters cyber-attacks, and mitigation plans are necessary, especially in smart energy grids. Additionally, due to the number of sensors, there is increased traffic for transmitting and processing acquired data to the cloud, which becomes a bottleneck due to bandwidth limitations. Moreover, SCADA-regulated smart energy systems are more exposed to security threats [3,12,14,43,45]. Some examples of cyber-attacks are described in [3,13], such as data manipulation, false data injection, energy theft through hacking the energy meters or tampering their operating system. Furthermore, phishing or man-in-the-middle, spoofing, Sybil, eavesdropping or side channel attacks can occur in a smart grid (SG) [1,6,12,14,23,43]. Additionally, the complexity of the interconnected devices in a smart grid (SG) can cause risks, as a loophole in one device can affect the entire system [11]. Stuxnet or Duqu attacks can vandalize industrial control systems, they are hazardous, but they bring with them little chance of spreading [5,63]. In 2016, the Dyn cyber-attack infected and hijacked innumerable IoT devices [11]. The cyber-attacks can disrupt the power grid even of a country. Therefore, to achieve a stable and reliable smart grid (SG), cyber detection and protection measures are becoming crucial [16].

Cyber-Threat Counter Measures

The Defense Advanced Research Projects Agency (DARPA) base the Internet of Things (IoT) security shield, which can impact security beyond the internet itself, on four principles: authentication, confidentiality, integrity and availability [11,43]. Among measures taken to counter cyber-attacks in IoT-based smart grids (SGs) worth mentioning are:

- Limited physical access to the IoT devices,
- Physical access to the devices monitored,
- Avoiding direct connecting IoT devices to the Internet,

- Proxy-based access system implementation,
- Secure remote access mechanism,
- Side-channel protection,
- Firmware protection,
- Secure operating system,
- Network security protocol-supported mechanism,
- Periodical security testing,
- Implementation of crypto mechanism [3].

In addition, the implementation of physically unclonable function (PUF) as the root-of-trust hardware helps smart grid (SG) systems in protecting devices, data and services protection [14]. Another solution is an intrusion detection system (IDS) inspired by recurrent neural networks and based on a deep learning approach [1,5].

7. Internet of Energy (IoE) Concept

Traditional centralized energy sector, with its low efficiency and reliability issues, has been tackled with the introduction of IoT resulting in the concept of the Internet of Energy (IoE). The term Energy Internet (also named Internet of Energy) was first introduced in 2011 by Jeremy Rifkin in his book "*The third industrial revolution*" [38,64]. Smart grid (SG) systems create a modern power network called IoE [25,57,65–67]. It is developing rapidly and has developed in smart cities creating urban Energy Internet. On a large-scale, global Energy Internet can also be distinguished [68]. In the IoE, large-scale RESs are the main energy supply; therefore, it requires a reliable network to support energy collection, storage and distribution. Additionally, micro-scale energy producers need to be linked to balance energy supply and demand [8,69]. IoT applications in the energy sector create a specific field IoE. For example, in smart commercial buildings it enables improved control and energy consumption optimization [9,70,71].

It can be noted that the Internet of Energy is a prosumer-centric concept [72].

The Internet of Energy (IoE) is expected to consist of five pillars, namely:

- The shift from traditional to renewable energy sources (RESs) as main energy production sources,
- The transformation of building into smart buildings by means of the Internet of Things (IoT) with the ability to sell excess energy to the grid,
- The deployment of storage technologies for better flexibility and efficient energy distribution within the grid,
- The transformation from a centralized system to a decentralized one based on the existing infrastructure,
- The electrification of the transport system in order to become independent from liquid fuels (e.g., oil and gasoline).

As mentioned in [62], several application modes of the Internet of Energy (IoE) have been formed, such as "park-level energy internet, park-level agricultural energy internet, fishery energy internet, commercial energy internet, rail transit energy internet and social energy internet".

In 2008 the German federal ministry for economic affairs launched a pilot project to build E-Energy. Other countries followed Germany in order to tackle the digitalization in the power sector. The architecture of Internet of Energy (IoE) is similar to that of IoT. It also consists of three layers: the physical layer with smart devices and other terminal devices, such as micro grids, electric vehicles (EVs), RES technologies; the data layer (including routers, Big Data and Blockchains); and finally, the operation layer, with its trade platforms, user interfaces and service-oriented energy platform [73,74].

The Internet of Energy (IoE) is boosting the rapid development of clean and renewable energy, thereby contributing to the achievement of the net-zero emission goal as well as sustainable development goals. The United Nations' seventh sustainable development goal aims at affordable and clean energy. Among goal targets that are mentioned, for example, are the substantially increased share of renewable energy sources (RESs) in global energy production and doubling the global pace of energy efficiency growth by 2030.

8. Blockchain in IoE

Although IoT provides various solutions for smart grid (SG) management and the Internet of Energy as a peer-to-peer network, it also brings vulnerabilities. These are mainly security issues, which can undermine the system's reliability. Continuous growth in the number of prosumers in the grid make them an important part in energy trading. All energy trading parties are involved in trading (producers, prosumers and consumers), which requires reliable and secure transactions in a more and more decentralized system. A promising technology that is able to counter the P2P security risks is a distributer ledger technology (DLT) [3,19,75–79].

One of most recognizable DLT technologies is a blockchain (BC), which can tackle smart transactions [80]. Others include Tangle, Hashgraph, Sidechain, Ethereum or Hyperledger [25]. A blockchain allows for the storage and data processing of transactions over the internet without the involvement of third parties (e.g., banks) [81]. It was first described by Satoshi Nakamoto in 2008 and introduced as a trading platform for Bitcoin [11,18,27,82–86]. The global revenue for enterprise applications of BCs in 2016 accounted for around USD 2.5 billion and is expected to reach USD 19.9 billion in 2025 (CAGR 26.2%) [85].

BC transaction records are stored in blocks that make up the data information, hash functions and hash of the previous blocks. Hash is simply a mathematical calculation required for a blockchain calculation, thus, fulfilling security requirements. Hash allows for block identification and the details it contains and is always unique. It also helps in blocks' traceability, making all BC transactions visible to its participants. Hashing enables encryption of data in a block [6,14,63]. Each block has a block id, timestamp, cryptographic hash of a previous block, as well as a digital signature. A new block (new transaction) is added to the one before, creating a chain of interconnected blocks. The records stored in blocks cannot be altered, as any change in a block requires a change in all subsequent blocks. This mechanism is a great security advantage of a blockchain [13,40,43,87,88]. Blockchain transactions are based on smart contracts between peers who verify the transaction without third parties' interference. Every network participant can verify the transaction by accessing their ledger [7,89]. BC network participants are called *miners* [11,88]. Figure 6 shows the main types of BC.

There are two main types of BC, public and private [18]. In a public blockchain, anyone can join the BC and create new blocks. In this type of blockchain, the PoW consensus protocol is being used. In other words, everyone can take part in the consensus process as long as they were checked as a node. This type of blockchain is mainly used in cryptocurrencies. In a private (or enterprise, consortium) type, the owner of a blockchain restricts the access. Only a few users are allowed to verify and add to the BC; they are managing the consensus process for the entire network [14,43,87,90,91]. On the other hand, in a private/permissioned blockchain, control and management are required to a certain level. The reliability of nodes is ensured when meeting certain conditions ruled by the network initiator. Only the nodes accepted by the network initiator are added as participants [82]. This type of blockchain offers a higher degree of privacy, confidentiality and security, which is key in densely deployed Internet of Energy (IoE) networks [14].

Hashing (e.g., SHA256 algorithm) in a blockchain improves the BC security; however, this is not enough to counter cyber-attacks [81]. Either in a public or a private BC, there must be a consensus network. In order to achieve a consensus, different approaches are used [11,92]. Those consensus algorithms can be applied to the transaction at any time before adding to the chain. There are four consensus algorithms:

- Proof of Work (PoW),
- Proof of Stake (PoS),
- Proof of Authority (PoA),
- Practical Byzantine Fault Tolerance (PBFT) [1,87,91,93,94].

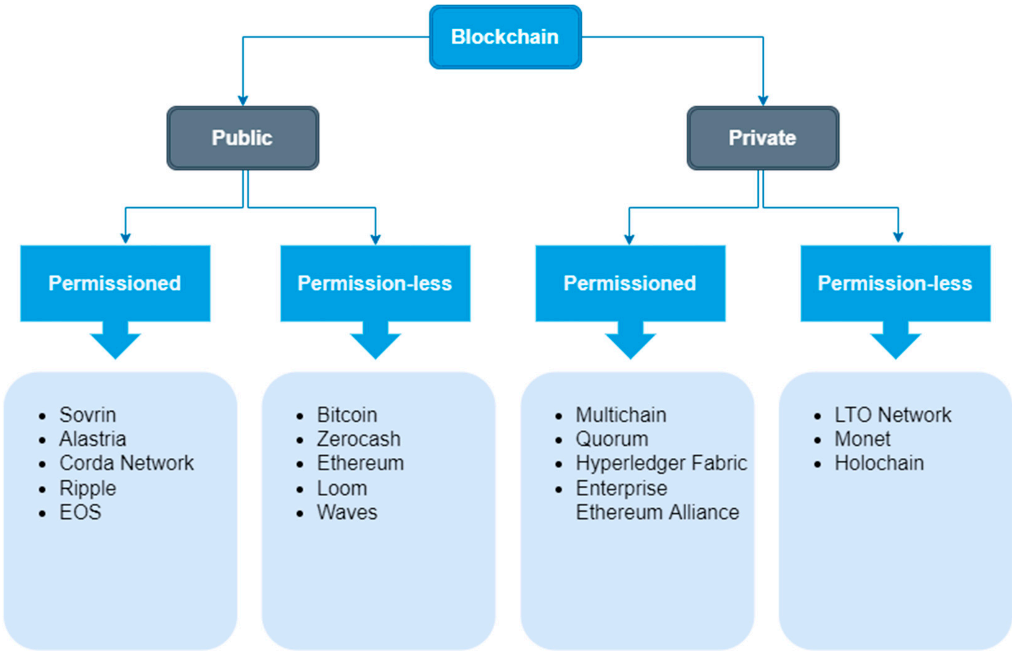

Figure 6. Types of blockchain.

In the Proof of Work algorithm, the system creates a puzzle ("guess the zeros") that needs to be solved by miners in order to have the block accepted. This consensus protocol is usually used in public permission-less frameworks [11,87,91].

The Proof of Stake algorithm is based on a deterministic choosing of a different block's producer. The miners take transaction fees in such a way so they can build a loyal node (high-stake node) [11,87].

The Proof of Authority algorithm allows the trusted users (approved accounts) to offer new transactions; this makes verifying much faster [87,91].

Practical Byzantine Fault Tolerance algorithm is based on the amount of fault tolerance [11,87,91].

When choosing the right consensus protocol, it is essential for BC developers to know exactly how they work and what the differences, opportunities and limitations for their easier implementation are [6].

Among blockchain advantages worth mentioning are anonymity, the transparency of transactions, decentralization and reliability, which are essential in the energy sector. As a result of globalization, sustainability goals (such as net-zero emissions) and energy security, due to various geopolitical crises in the energy sector, is moving towards a decentralized system with a deregulated market structure. Decentralized blockchain technology supported by IoT is, thus, opening new possibilities to that transformation [6]. As IoE networks are very dense for a cost-effective deployment of BC-based IoE networks, a layered architecture has been implemented similar to that in a smart grid (SG). This solution provides "maximum versatility for potential expansions and developers can substitute or install any new module without disrupting the rest of the infrastructure" [14].

A blockchain can support the transaction records storage process of any action in the smart grid (SG) by means of blocks in a blockchain. It has been shown that an IoT-based blockchain is essential for securing online monitoring. Therefore, an IoT-based blockchain can help to identify data loss or interruption in the network [13]. Blockchain-based systems provide security through cryptography, decentralization by means of consensus mechanism and transparency due to a distributed ledger system, which together with smart contracts will enable market platform decentralization [95]. Blockchains can resolve limitations in transactive energy systems (TES). Thanks to their ability to protect customer data, blockchains can streamline a multi-party settlement on a local level (Home Area Networks

(HANs) or Neighbor Area Networks (NANs)), customize complex contracts on a mass scale and direct offers on different devices. This brings new possibilities in the energy sector because they can allow electricity consumers and producers (prosumers) at the edge of the network for mass bidirectional transactions [28].

As with almost every new technology, standardization is an important factor. Asif [14] lists several standards concerning DLT/blockchain, such as IEEE P2418 series or ISO 307. Furthermore, the author mentions the Enterprise Ethereum Alliance (EEA) working on transparency, harmonization and interoperability on the global market. The International Telecommunication Union's Standardization Sector (ITU-T) has developed a focus group responsible for the recognition and review of distributed ledger applications and services, but also for creating best practices and recommendations. The World Wide Web Consortium (W3C) on the other hand is working on ISO 20022-based message format standards and creates guidelines for storage use in both public and private blockchains. A reference architecture for IoT can be found in ISO/IEC 30141; it includes the ISO/IEC 27400:2022 Cybersecurity—IoT security and privacy—guidelines provide guidelines on risks, principles and controls for the security and privacy of Internet of Things (IoT) solutions. The selected standards are presented in Table 2.

Table 2. Selected International Organization for Standardization blockchain standards.

Standard	Document Status	Scope
ISO/CD TR 6039	Under development	Blockchain and distributed ledger technologies—identifiers of subjects and objects for the design of blockchain systems.
ISO 22739:2020	Published	Provides fundamental terminology for blockchain and distributed ledger technologies.
ISO/CD 22739	Under development (2nd edition)	Blockchain and distributed ledger technologies—vocabulary.
ISO/TR 23244:2020	Published	Provides an overview of privacy and personally identifiable information (PII) protection as applied to blockchain and distributed ledger technologies (DLT) systems
ISO/TR 23249:2022	Published	Provides an overview of existing DLT systems for identity management, i.e., the mechanisms by which one or more entities can create, receive, modify, use and revoke a set of identity attributes.
ISO 23257:2022	Published	Specifies a reference architecture for distributed ledger technology (DLT) systems including blockchain systems. The reference architecture addresses concepts, cross-cutting aspects, architectural considerations, and architecture views, including functional components, roles, activities, and their relationships for blockchain and DLT.
ISO/TS 23258:2021	Published	Specifies a taxonomy and an ontology for blockchain and distributed ledger technologies (DLT). The taxonomy includes a taxonomy of concepts, a taxonomy of DLT systems and a taxonomy of application domains, purposes and economic activity sections for use cases. The ontology includes classes and attributes as well as relations between concepts.
ISO/TR 23455:2019	Published	Provides an overview of smart contracts in BC/DLT systems; describing what smart contracts are and how they work. It also discusses the methods of interaction between multiple smart contracts. This document focuses on the technical aspects of smart contracts. Smart contracts for legally binding use and applications will only be briefly mentioned in this document.
ISO/TR 23576:2020	Published	Discusses the threats, risks, and controls related to systems and asset information.
ISO/TS 23635:2022	Published	Provides guiding principles and a framework for the governance of DLT systems.
ISO/CD TR 23644	Under development	Blockchain and distributed ledger technologies—an overview of trust anchors for DLT-based identity management (TADIM).
ISO/CD TR 24374	Under development	Information technology—security techniques—DLT and blockchain for financial services.

Source: Based on ISO ICS Code 35.030 (https://www.iso.org/ics/35.030/x/ (accessed on 15 October 2022)).

In the US, a company called Exergy was the first that applied blockchain to a transactive grid, the Brooklyn Microgrid, in 2016. There are also businesses such as Grid+, LO3 energy or Power Ledger that offer new metering and billing BC solutions [96]. Electron is a United Kingdom company applying BC technology to the energy sector [2]. Another startup is the Power Ledger in Australia [35]. The TRANSAX platform for forward-trading energy exchange was described in [97]. Whereas, in [98], a secure blockchain-enabled dynamic monitoring and decision system was proposed for a minimal-information exchange framework. ZipZap is a novel tokenization blockchain for local energy exchanges described in [99]. In addition, ref. [100] proposed a blockchain-based system model for smart meter network communication, which uses elliptic curve cryptography (ECC) and digital signature over a home area network (HAN). Whereas [101] investigated smart grid (SG) and energy transactions in a P2P network in a local community in the UK.

9. Conclusions

The increased integration of renewable energy sources, storage systems, electric vehicles, distributed generation and microgrids in smart grids (SGs) make traditional centralized power management no longer attractive. The reasons for this are the system's disadvantages, such as the cost, security issues, control of a complex network, energy trading and energy management [6].

IoT combined with blockchain technology has the potential to increase transparency and trust between different stakeholders, as it offers both privacy and confidentiality. It can also enhance data security thorough encryption, cryptography and consensus protocols. Moreover, this combination in the new decentralized energy system can minimize transaction costs, support processes automation and facilitate the active participation of small consumers and prosumers in the smart grid (SG) [87,94]. Blockchain is an emerging technology that can use enterprise data with the use of secure transactions between parties. Blockchain-enabled systems are a new trend rising fast in the area of engineering [1].

The transformation currently taking place in decentralization in the energy sector favors customers and is, thus, more consumer-centric and changing the attitude towards customer satisfaction.

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Abbreviations

Alphabetical list of abbreviations used within the paper:

AI	Artificial Intelligence
AMI	Advanced Metering Infrastructure
BC	Blockchain
BDA	Big Data Analytics
BIPV	Building-Integrated Photovoltaics
CAGR	Compound Annual Growth Rate
CSV	Comma-Separated Values
DARPA	Defense Advanced Research Projects Agency
DC	Direct Current
DLT	Distributed ledger
ECC	Elliptic Curve Cryptography
EEA	Enterprise Ethereum Alliance
EV	Electric Vehicle
HAN	Home Area Network
HMI	Human Machine Interfaces
HVDC	High-Voltage Direct Current
IDS	Intrusion Detection system
IEEE	Institute of Electrical and Electronics Engineers
IoE	Internet of Energy
IoT	Internet of Things
ISO	International Organization for Standardization
ITU-T	The International Telecommunication Union's Standardization Sector
LAN	Local Area Network
LE	Low Energy
LoRa	Long Range
LPWAN	Low-Power Wide Area Network

LTE	Long-Term Evolution
MG	Microgrid
ML	Machine Learning
NAN	Neighbor Area Network
NB-IoT	Narrow-Band Internet of Things
NFC	Near-Field Communication
OSC	Organic Solar Cell
P2P	Peer-to-Peer
PBFT	Practical Byzantine Fault Tolerance
PCE	Power Conversion Efficiency
PII	Personally Identifiable Information
PoA	Proof of Authority
PoS	Proof of Stake
PoW	Proof of Work
PUF	Physically Unclonable Function
PVs	Photovoltaic panels
RES	Renewable Energy Sources
RFID	Radio-Frequency Identification
RTU	Remote Terminal Unit
SCADA	Supervisory Control and Data Acquisition
SG	Smart Grid
SM	Smart Metering
TADIM	Trust Anchors for DLT-based Identity Management
TES	Transactive Energy Systems
UPnP	Universal Plug and Play
V2G	Vehicle-to-Grid
W3C	World Wide Web Consortium
WAN	Wide Area Network
Wi-Fi	Wireless Fidelity
WPAN	Wireless Personal Area Network
WSN	Wireless Sensor Network

References

1. Ferrag, M.A.; Maglaras, L. DeepCoin: A Novel Deep learning and Blockchain-based Energy Exchange Framework for Smart Grids. *IEEE Trans. Eng. Manag.* **2020**, *67*, 1285–1297. [CrossRef]
2. Fadhel, N.; Lombardi, F.; Aniello, L.; Margheri, A.; Sassone, V. Towards a semantic modelling for threat analysis of IoT applications: A case study on transactive energy. In *IET Conference Publications*; Institution of Engineering and Technology: London, UK, 2019. [CrossRef]
3. Abir, S.M.A.A.; Anwar, A.; Choi, J.; Kayes, A.S.M. Iot-enabled smart energy grid: Applications and challenges. *IEEE Access* **2021**, *9*, 50961–50981. [CrossRef]
4. Raja Guru, R.; Kumar, P. Self-restrained energy grid with data analysis and blockchain techniques. In *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*; Taylor & Francis Group: Abingdon, UK, 2020; pp. 1–19. [CrossRef]
5. Hasan, M.K.; Alkhalifah, A.; Islam, S.; Babiker, N.B.M.; Habib, A.K.M.A.; Aman, A.H.M.; Hossain, M. Blockchain Technology on Smart Grid, Energy Trading, and Big Data: Security Issues, Challenges, and Recommendations. *Wirel. Commun. Mob. Comput.* **2022**, *2022*, 1–26. [CrossRef]
6. Al-Abri, T.; Onen, A.; Al-Abri, R.; Hossen, A.; Al-Hinai, A.; Jung, J.; Ustun, T.S. Review on Energy Application Using Blockchain Technology with an Introductions in the Pricing Infrastructure. *IEEE Access* **2022**, *10*, 80119–80137. [CrossRef]
7. Baig, M.J.A.; Iqbal, M.T.; Jamil, M.; Khan, J. Peer-to-Peer Energy Trading in a Micro-grid Using Internet of Things and Blockchain. *Electronics* **2021**, *25*, 39–49. [CrossRef]
8. Guan, Z.; Lu, X.; Yang, W.; Wu, L.; Wang, N.; Zhang, Z. Achieving efficient and Privacy-preserving energy trading based on blockchain and ABE in smart grid. *J. Parallel Distrib. Comput.* **2021**, *147*, 34–45. [CrossRef]
9. Hosseinian, H.; Shahinzadeh, H.; Gharehpetian, G.B.; Azani, Z.; Shaneh, M. Blockchain outlook for deployment of IoT in distribution networks and smart homes. *Int. J. Electr. Comput. Eng.* **2020**, *10*, 2787–2796. [CrossRef]
10. Khan, A.N.; Iqbal, N.; Ahmad, R.; Kim, D.H. Ensemble prediction approach based on learning to statistical model for efficient building energy consumption management. *Symmetry* **2021**, *13*, 405. [CrossRef]
11. Alshaikhli, M.; Elfouly, T.; Elharrouss, O.; Mohamed, A.; Ottakath, N. Evolution of Internet of Things from Blockchain to IOTA: A Survey. *IEEE Access* **2022**, *10*, 844–866. [CrossRef]
12. Eze, K.G.; Akujuobi, C.M.; Hunter, S.; Alam, S.; Musa, S.; Foreman, J. A Blockchain-based Security Architecture for the Internet of Things. *WSEAS Trans. Inf. Sci. Appl.* **2022**, *19*, 12–22. [CrossRef]
13. Baidya, S.; Potdar, V.; Pratim Ray, P.; Nandi, C. Reviewing the opportunities, challenges, and future directions for the digitalization of energy. *Energy Res. Soc. Sci.* **2021**, *81*, 102243. [CrossRef]
14. Asif, R.; Ghanem, K.; Irvine, J. Proof-of-puf enabled blockchain: Concurrent data and device security for internet-of-energy. *Sensors* **2021**, *21*, 28. [CrossRef] [PubMed]

15. Bregar, A. Implementation of a multi-agent multi-criteria negotiation protocol for self-sustainable smart grids. *J. Decis. Syst.* **2020**, *29* (Suppl. S1), 87–97. [CrossRef]
16. Çelik, D.; Meral, M.E.; Waseem, M. Investigation and analysis of effective approaches, opportunities, bottlenecks and future potential capabilities for digitalization of energy systems and sustainable development goals. *Electr. Power Syst. Res.* **2022**, *211*, 108251. [CrossRef]
17. Stanelyte, D.; Radziukyniene, N.; Radziukynas, V. Overview of Demand-Response Services: A Review. *Energies* **2022**, *15*, 1659. [CrossRef]
18. Juszczyk, O.; Shahzad, K. Blockchain Technology for Renewable Energy: Principles, Applications and Prospects. *Energies* **2022**, *15*, 4603. [CrossRef]
19. Rejeb, A.; Keogh, J.G.; Treiblmaier, H. Leveraging the Internet of Things and blockchain technology in Supply Chain Management. *Future Internet* **2019**, *11*, 161. [CrossRef]
20. Alexopoulos, K.; Koukas, S.; Boli, N.; Mourtzis, D. Architecture and development of an Industrial Internet of Things framework for realizing services in Industrial Product Service Systems. *Procedia CIRP* **2018**, *72*, 880–885. [CrossRef]
21. Forsstrom, S.; Butun, I.; Eldefrawy, M.; Jennehag, U.; Gidlund, M. Challenges of Securing the Industrial Internet of Things Value Chain. In Proceedings of the 2018 Workshop on Metrology for Industry 4.0 and IoT, MetroInd 4.0 and IoT 2018—Proceedings, Brescia, Italy, 16–18 April 2018; Institute of Electrical and Electronics Engineers Inc.: New York, NY, USA, 2018; pp. 218–223. [CrossRef]
22. Ometov, A.; Molua, O.L.; Komarov, M.; Nurmi, J. A Survey of Security in Cloud, Edge, and Fog Computing. *Sensors* **2022**, *22*, 927. [CrossRef]
23. Aggarwal, S.; Kumar, N.; Tanwar, S.; Alazab, M. A Survey on Energy Trading in the Smart Grid: Taxonomy, Research Challenges and Solutions. *IEEE Access* **2021**, *9*, 116231–116253. [CrossRef]
24. Motlagh, N.H.; Mohammadrezaei, M.; Hunt, J.; Zakeri, B. Internet of things (IoT) and the energy sector. *Energies* **2020**, *13*, 494. [CrossRef]
25. Hosseinnezhad, V.; Hayes, B.; O'Regan, B.; Siano, P. Practical Insights to Design a Blockchain-Based Energy Trading Platform. *IEEE Access* **2021**, *9*, 154827–154844. [CrossRef]
26. Jaiswal, R.; Davidrajuh, R.; Rong, C. Fog computing for realizing smart neighborhoods in smart grids. *Computers* **2020**, *9*, 76. [CrossRef]
27. Kumari, A.; Gupta, R.; Tanwar, S.; Kumar, N. Blockchain and AI amalgamation for energy cloud management: Challenges, solutions, and future directions. *J. Parallel Distrib. Comput.* **2020**, *143*, 148–166. [CrossRef]
28. Olivares-Rojas, J.C.; Reyes-Archundia, E.; Gutierrez-Gnecchi, J.A.; Molina-Moreno, I.; Cerda-Jacobo, J.; Mendez-Patino, A. A transactive energy model for smart metering systems using blockchain. *CSEE J. Power Energy Syst.* **2021**, *7*, 943–953. [CrossRef]
29. Khan, A.N.; Iqbal, N.; Rizwan, A.; Ahmad, R.; Kim, D.H. An ensemble energy consumption forecasting model based on spatial-temporal clustering analysis in residential buildings. *Energies* **2021**, *14*, 3020. [CrossRef]
30. Suciu, G.; Farao, A.; Bernardinetti, G.; Palamà, I.; Sachian, M.A.; Vulpe, A.; Vochin, M.-C.; Muresan, P.; Bampatsikos, M.; Muñoz, A.; et al. SAMGRID: Security Authorization and Monitoring Module Based on SealedGRID Platform. *Sensors* **2022**, *22*, 6527. [CrossRef]
31. Wójcicki, K.; Biegańska, M.; Paliwoda, B.; Górna, J. Internet of Things in Industry: Research Profiling, Application, Challenges and Opportunities—A Review. *Energies* **2022**, *15*, 1806. [CrossRef]
32. Corallo, A.; Latino, M.E.; Menegoli, M.; Pontrandolfo, P. A systematic literature review to explore traceability and lifecycle relationship. *Int. J. Prod. Res.* **2020**, *58*, 4789–4807. [CrossRef]
33. Donthu, N.; Kumar, S.; Mukherjee, D.; Pandey, N.; Lim, W.M. How to conduct a bibliometric analysis: An overview and guidelines. *J. Bus. Res.* **2021**, *133*, 285–296. [CrossRef]
34. Chen, X.; Chen, J.; Wu, D.; Xie, Y.; Li, J. Mapping the Research Trends by Co-word Analysis Based on Keywords from Funded Project. *Procedia Comput. Sci.* **2016**, *91*, 547–555. [CrossRef]
35. Jamil, F.; Iqbal, N.; Imran Ahmad, S.; Kim, D. Peer-to-Peer Energy Trading Mechanism Based on Blockchain and Machine Learning for Sustainable Electrical Power Supply in Smart Grid. *IEEE Access* **2021**, *9*, 39193–39217. [CrossRef]
36. Kumar, N.M.; Chand, A.A.; Malvoni, M.; Prasad, K.A.; Mamun, K.A.; Islam, F.R.; Chopra, S.S. Distributed energy resources and the application of ai, iot, and blockchain in smart grids. *Energies* **2020**, *13*, 5739. [CrossRef]
37. Laszka, A.; Dubey, A.; Walker, M.; Schmidt, D. Providing privacy, safety, and security in IoT-based transactive energy systems using distributed ledgers. In *ACM International Conference Proceeding Series*; Association for Computing Machinery: New York, NY, USA, 2017. [CrossRef]
38. Zhang, X.; Xu, K.; He, M. Development status and some considerations on Energy Internet construction in Beijing-Tianjin-Hebei region. *Heliyon* **2022**, *8*, e08722. [CrossRef] [PubMed]
39. Bracciale, L.; Loreti, P.; Raso, E.; Bianchi, G.; Gallo, P.; Sanseverino, E.R. A Privacy-Preserving Blockchain Solution to Support Demand Response in Energy Trading. In Proceedings of the MELECON 2022—IEEE Mediterranean Electrotechnical Conference, Palermo, Italy, 14–16 June 2022; Institute of Electrical and Electronics Engineers Inc.: New York, NY, USA, 2022; pp. 677–682. [CrossRef]
40. Lu, W.; Ren, Z.; Xu, J.; Chen, S. Edge Blockchain Assisted Lightweight Privacy-Preserving Data Aggregation for Smart Grid. *IEEE Trans. Netw. Serv. Manag.* **2021**, *18*, 1246–1259. [CrossRef]

41. Pieroni, A.; Scarpato, N.; di Nunzio, L.; Fallucchi, F.; Raso, M. Smarter City: Smart energy grid based on Blockchain technology. *Int. J. Adv. Sci. Eng. Inf. Technol.* **2018**, *8*, 298–306. [CrossRef]
42. Wang, D.; Wang, H.; Fu, Y. Blockchain-based IoT device identification and management in 5G smart grid. *Eurasip J. Wirel. Commun. Netw.* **2021**, *2021*, 1–19. [CrossRef]
43. Dehalwar, V.; Kolhe, M.L.; Deoli, S.; Jhariya, M.K. Blockchain-based trust management and authentication of devices in smart grid. *Clean. Eng. Technol.* **2022**, *8*, 100481. [CrossRef]
44. Wu, Y.; Wu, Y.; Guerrero, J.M.; Vasquez, J.C. Decentralized transactive energy community in edge grid with positive buildings and interactive electric vehicles. *Int. J. Electr. Power Energy Syst.* **2022**, *135*, 107510. [CrossRef]
45. Minh, Q.N.; Nguyen, V.H.; Quy, V.K.; Ngoc, L.A.; Chehri, A.; Jeon, G. Edge Computing for IoT-Enabled Smart Grid: The Future of Energy. *Energies* **2022**, *15*, 6140. [CrossRef]
46. Singh, R.; Akram, S.V.; Gehlot, A.; Buddhi, D.; Priyadarshi, N.; Twala, B. Energy System 4.0: Digitalization of the Energy Sector with Inclination towards Sustainability. *Sensors* **2022**, *22*, 6619. [CrossRef] [PubMed]
47. González, I.; Calderón, A.J.; Folgado, F.J. IoT real time system for monitoring lithium-ion battery long-term operation in microgrids. *J. Energy Storage* **2022**, *51*, 104596. [CrossRef]
48. Gomes De Melo, G.C.; Torres, I.C.; Bezzera Queiroz De Araújo, Í.; Brito, D.B.; de Andrade Barboza, E. A Low-Cost IoT System for Real-Time Monitoring of Climatic Variables and Photovoltaic Generation for Smart Grid Application A Low-Cost IoT System for Real-Time Monitoring of Climatic Variables and Photovoltaic Generation for Smart. *Sensors* **2021**, *21*, 3293. [CrossRef]
49. Shahzad, Y.; Javed, H.; Farman, H.; Ahmad, J.; Jan, B.; Zubair, M. Internet of Energy: Opportunities, applications, architectures and challenges in smart industries. *Comput. Electr. Eng.* **2020**, *86*, 106739. [CrossRef]
50. Zhang, J. Distributed network security framework of energy internet based on internet of things. *Sustain. Energy Technol. Assess.* **2021**, *44*, 101051. [CrossRef]
51. Wu, Y.; Wu, Y.; Guerrero, J.M.; Vasquez, J.C. A comprehensive overview of framework for developing sustainable energy internet: From things-based energy network to services-based management system. *Renew. Sustain. Energy Rev.* **2021**, *150*, 111409. [CrossRef]
52. Shahinzadeh, H.; Mirhedayati, A.S.; Shaneh, M.; Nafisi, H.; Gharehpetian, G.B.; Moradi, J. Role of joint 5G-IoT framework for smart grid interoperability enhancement. In Proceedings of the 2020 15th International Conference on Protection and Automation of Power Systems, IPAPS 2020, Shiraz University, Shiraz, Iran, 30–31 December 2020; Institute of Electrical and Electronics Engineers Inc.: New York, NY, USA, 2020; pp. 12–18. [CrossRef]
53. Moradi, J.; Shahinzadeh, H.; Nafisi, H.; Marzband, M.; Gharehpetian, G.B. Attributes of Big Data Analytics for Data-Driven Decision Making in Cyber-Physical Power Systems. In Proceedings of the 2020 14th International Conference on Protection and Automation of Power Systems, IPAPS 2020, Amirkabir University of Technology (Tehran Polytechnic), Tehran, Iran, 31 December 2019–1 January 2020; Institute of Electrical and Electronics Engineers Inc.: New York, NY, USA, 2019; pp. 83–92. [CrossRef]
54. de Arquer Fernández, P.; Angel Fernández Fernández, M.; Luis, J.; Candás, C.; Arboleya Arboleya, P. An IoT open source platform for photovoltaic plants supervision. *Electr. Power Energy Syst.* **2021**, *125*, 106540. [CrossRef]
55. Wu, Y.; Wu, Y.; Cimen, H.; Vasquez, J.C.; Guerrero, J.M. Towards collective energy Community: Potential roles of microgrid and blockchain to go beyond P2P energy trading. *Appl. Energy* **2022**, *314*, 119003. [CrossRef]
56. Mogadem, M.M.; Li, Y.; Meheretie, D.L. A survey on internet of energy security: Related fields, challenges, threats and emerging technologies. *Clust. Comput.* **2022**, *25*, 2449–2485. [CrossRef]
57. Parvin, K.; Hannan, M.A.; Hui Mun, L.; Hossain Lipu, M.S.; Abdolrasol, M.G.M.; Jern Ker, P.; Muttaqi, K.M.; Dong, Z. The future energy internet for utility energy service and demand-side management in smart grid: Current practices, challenges and future directions. *Sustain. Energy Technol. Assess.* **2022**, *53*, 102648. [CrossRef]
58. Prasanna Rani, D.D.; Suresh, D.; Rao Kapula, P.; Mohammad Akram, C.H.; Hemalatha, N.; Kumar Soni, P. IoT based smart solar energy monitoring systems. *Mater. Today Proc.* **2021**. [CrossRef]
59. Priyadharsini, K.; Dinesh Kumar, J.R.; Ganesh Babu, C.; Srikanth, A.; Sounddar, V.; Senthamilselvan, M. Elegant method to improve the efficiency of remotely located solar panels using IoT. In *Materials Today: Proceedings*; Elsevier Ltd.: Singapore, 2021; pp. 8094–8104. [CrossRef]
60. Ma, R.; Yan, C.; Fong, P.W.K.; Yu, J.; Liu, H.; Yin, J.; Huang, J.; Lu, X.; Yan, H.; Li, G. In situ and ex situ investigations on ternary strategy and co-solvent effects towards high-efficiency organic solar cells. *Energy Environ. Sci.* **2022**, *15*, 2479–2488. [CrossRef]
61. Wang, D.; Li, Y.; Zhou, G.; Gu, E.; Xia, R.; Yan, B.; Yao, J.; Zhu, H.; Lu, X.; Yip, H.-L.; et al. High-performance see-through power windows. *Energy Environ. Sci.* **2022**, *15*, 2629–2637. [CrossRef]
62. Long, H.; Fu, X.; Kong, W.; Chen, H.; Zhou, Y.; Yang, F. Key technologies and applications of rural energy internet in China. *Inf. Process. Agric.* **2022**. [CrossRef]
63. Xu, W.; Li, J.; Dehghani, M.; GhasemiGarpachi, M. Blockchain-based secure energy policy and management of renewable-based smart microgrids. *Sustain. Cities Soc.* **2021**, *72*, 103010. [CrossRef]
64. Geng, J.; Du, W.; Yang, D.; Chen, Y.; Liu, G.; Fu, J.; He, G.; Wang, J.; Chen, H. Construction of energy internet technology architecture based on general system structure theory. *Energy Rep.* **2021**, *7*, 10–17. [CrossRef]
65. Hu, H.; Ou, J.; Qian, B.; Luo, Y.; He, P.; Zhou, M.; Chen, Z. A Practical Anonymous Voting Scheme Based on Blockchain for Internet of Energy. *Secur. Commun. Netw.* **2022**, *2022*, 1–15. [CrossRef]

66. Perera, A.T.D.; Wang, Z.; Nik, V.M.; Scartezzini, J.L. Towards realization of an Energy Internet: Designing distributed energy systems using game-theoretic approach. *Appl. Energy* **2021**, *283*, 116349. [CrossRef]
67. Swathi, G.C.; Kumar, G.K.; Kumar, A.P.S. Estimating Botnet Impact on IoT/IoE networks using Traffic flow Features. *Comput. Electr. Eng.* **2022**, *102*, 108209. [CrossRef]
68. Kong, X.; Zhao, X.; Wang, C.; Duan, Q.; Sha, G.; Liu, L. Promote the international development of Energy Internet technology standards based on key competition mode. *Sustain. Cities Soc.* **2022**, *86*, 104151. [CrossRef]
69. Ma, H.; Zhang, Y.; Shen, M. Application and prospect of supercapacitors in Internet of Energy (IOE). *J. Energy Storage* **2021**, *44*, 103299. [CrossRef]
70. Song, Y.J.; Lee, J.K. A blockchain-based fog-enabled energy cloud in internet of things. *J. Logist. Inform. Serv. Sci.* **2020**, *7*, 45–64. [CrossRef]
71. Song, Y.J.; Lee, J.K. A blockchain and internet of things based architecture design for energy transaction. *J. Syst. Manag. Sci.* **2020**, *10*, 122–140. [CrossRef]
72. Wu, Y.; Wu, Y.; Guerrero, J.M.; Vasquez, J.C. Digitalization and decentralization driving transactive energy Internet: Key technologies and infrastructures. *Int. J. Electr. Power Energy Syst.* **2021**, *126*, 106593. [CrossRef]
73. Laroussi, I.; Huan, L.; Xiusheng, Z. How will the internet of energy (IoE) revolutionize the electricity sector? A techno-economic review. *Mater. Today Proc.* **2022**. [CrossRef]
74. Zhihong, J.; Jian, H.; Wenzhou, L.; Zhe, C.; Ning, L.; Siyuan, W.; Xiao, Z.; Chang, L. Energy internet—A new driving force for sustainable urban development. In *Energy Procedia*; Elsevier Ltd.: Singapore, 2018; pp. 1206–1211. [CrossRef]
75. Khorasany, M.; Dorri, A.; Razzaghi, R.; Jurdak, R. Lightweight Blockchain Framework for Location-aware Peer-to-Peer Energy Trading. *Int. J. Electr. Power Energy Syst.* **2020**, *127*, 106610. [CrossRef]
76. Merrad, Y.; Habaebi, M.H.; Toha, F.; Islam, M.R.; Gunawan, T.S.; Mesri, M. Fully Decentralized, Cost-Effective Energy Demand Response Management System with a Smart Contracts-Based Optimal Power Flow Solution for Smart Grids. *Energies* **2022**, *15*, 4461. [CrossRef]
77. Moniruzzaman, M.; Yassine, A.; Benlamri, R. Blockchain-based Mechanisms for Local Energy Trading in Smart Grids. In Proceedings of the HONET-ICT 2019—IEEE 16th International Conference on Smart Cities: Improving Quality of Life using ICT, IoT and AI, Charlotte, NC, USA, 6–9 October 2019; Institute of Electrical and Electronics Engineers Inc.: New York, NY, USA, 2019; pp. 110–114. [CrossRef]
78. Dietrich, F.; Ge, Y.; Turgut, A.; Louw, L.; Palm, D. Review and analysis of blockchain projects in supply chain management. *Procedia Comput. Sci.* **2021**, *180*, 724–733. [CrossRef]
79. Esmaeilian, B.; Sarkis, J.; Lewis, K.; Behdad, S. Blockchain for the future of sustainable supply chain management in Industry 4.0. *Resour. Conserv. Recycl.* **2020**, *163*, 105064. [CrossRef]
80. Kapassa, E.; Themistocleous, M.; Christodoulou, K.; Iosif, E. Blockchain application in internet of vehicles: Challenges, contributions and current limitations. *Future Internet* **2021**, *13*, 313. [CrossRef]
81. Merrad, Y.; Habaebi, M.H.; Islam, M.R.; Gunawan, T.S.; Mesri, M. Robust Decentralized Proof of Location for Blockchain Energy Applications Using Game Theory and Random Selection. *Sustainability* **2022**, *14*, 6123. [CrossRef]
82. Gür, A.Ö.; Öksüzer, Ş.; Karaarslan, E. Blockchain Based Metering and Billing System Proposal with Privacy Protection for the Electric Network. In Proceedings of the 7th International Istanbul Smart Grids and Cities Congress and Fair, ICSG 2019—Proceedings, Istanbul, Turkey, 25–26 April 2019; Institute of Electrical and Electronics Engineers Inc.: New York, NY, USA, 2019; pp. 204–208. [CrossRef]
83. Kolahan, A.; Maadi, S.R.; Teymouri, Z.; Schenone, C. Blockchain-based solution for energy demand-side management of residential buildings. *Sustain. Cities Soc.* **2021**, *75*, 103316. [CrossRef]
84. Lombardi, F.; Aniello, L.; de Angelis, S.; Margheri, A.; Sassone, V. A blockchain-based infrastructure for reliable and cost-effective IoT-aided smart grids. In Proceedings of the IET Conference Publications, London, UK, 28–29 March 2018; Institution of Engineering and Technology: London, UK, 2018. [CrossRef]
85. Luong, N.C.; Xiong, Z.; Wang, P.; Niyato, D. Optimal Auction For Edge Computing Resource Management in Mobile Blockchain Networks: A Deep Learning Approach. In Proceedings of the 2018 IEEE International Conference on Communications (ICC), Kansas City, MO, USA, 20–24 May 2018; pp. 1–6.
86. Wang, S.; Liu, X.; Ha, J. Optimal IoT-based decision-making of smart grid dispatchable generation units using blockchain technology considering high uncertainty of system. *Ad Hoc Netw.* **2022**, *127*, 102751. [CrossRef]
87. Hasankhani, A.; Mehdi Hakimi, S.; Shafie-khah, M.; Asadolahi, H. Blockchain technology in the future smart grids: A comprehensive review and frameworks. *Int. J. Electr. Power Energy Syst.* **2021**, *129*, 106811. [CrossRef]
88. Florea, B.C.; Taralunga, D.D. Blockchain IoT for smart electric vehicles battery management. *Sustainability* **2020**, *12*, 3984. [CrossRef]
89. Chaudhary, R.; Jindal, A.; Aujla, G.S.; Aggarwal, S.; Kumar, N.; Choo, K.K.R. BEST: Blockchain-based secure energy trading in SDN-enabled intelligent transportation system. *Comput. Secur.* **2019**, *85*, 288–299. [CrossRef]
90. Sisi, Z.; Souri, A. Blockchain technology for energy-aware mobile crowd sensing approaches in Internet of Things. *Trans. Emerg. Telecommun. Technol.* **2021**, e4217. [CrossRef]
91. Musleh, A.S.; Yao, G.; Muyeen, S.M. Blockchain Applications in Smart Grid-Review and Frameworks. *IEEE Access* **2019**, *7*, 86746–86757. [CrossRef]

92. Valtanen, K.; Backman, J.; Yrjola, S. Blockchain-Powered Value Creation in the 5G and Smart Grid Use Cases. *IEEE Access* **2019**, *7*, 25690–25707. [CrossRef]
93. Mylrea, M.; Gourisetti, S.N.G. Blockchain for Supply Chain Cybersecurity, Optimization and Compliance. In Proceedings of the Resilience Week 2018, RWS 2018, Denver, CO, USA, 20–23 August 2018; Institute of Electrical and Electronics Engineers Inc.: Piscataway, NJ, USA, 2018; pp. 70–76. [CrossRef]
94. Nour, M.; Chaves-Avila, J.P.; Sanchez-Miralles, A. Review of Blockchain Potential Applications in the Electricity Sector and Challenges for Large Scale Adoption. *IEEE Access* **2022**, *10*, 47384–47418. [CrossRef]
95. Mengelkamp, E.; Notheisen, B.; Beer, C.; Dauer, D.; Weinhardt, C. A blockchain-based smart grid: Towards sustainable local energy markets. In *Computer Science—Research and Development*; Springer: Berlin, Germany, 2018; pp. 207–214. [CrossRef]
96. Meeuw, A.; Schopfer, S.; Wörner, A.; Tiefenbeck, V.; Ableitner, L.; Fleisch, E.; Wortmann, F. Implementing a blockchain-based local energy market: Insights on communication and scalability. *Comput. Commun.* **2020**, *160*, 158–171. [CrossRef]
97. Laszka, A.; Eisele, S.; Dubey, A.; Karsai, G.; Kvaternik, K. TRANSAX: A Blockchain-based Decentralized Forward-Trading Energy Exchange for Transactive Microgrids. In Proceedings of the 2018 IEEE 24th International Conference on Parallel and Distributed Systems (ICPADS), Singapore, 11–13 December 2018.
98. Lauer, M.; Jaddivada, R.; Ilic, M. Secure blockchain-enabled DyMonDS design. In *ACM International Conference Proceeding Series*; Association for Computing Machinery: New York, NY, USA, 2019; pp. 191–198. [CrossRef]
99. Munoz, M.F.; Zhang, K.; Amara, F. ZipZap: A Blockchain Solution for Local Energy Trading. In Proceedings of the 2022 IEEE International Conference on Blockchain and Cryptocurrency (ICBC), Shanghai, China, 2–5 May 2022; Available online: http://arxiv.org/abs/2202.13450 (accessed on 22 September 2022).
100. Shukla, S.; Thakur, S.; Breslin, J.G. Secure communication in smart meters using elliptic curve cryptography and digital signature algorithm. In Proceedings of the 2021 IEEE International Conference on Cyber Security and Resilience, CSR 2021, Virtual. 26–28 July 2021; Institute of Electrical and Electronics Engineers Inc.: New York, NY, USA, 2021; pp. 261–266. [CrossRef]
101. Lüth, A.; Zepter, J.M.; Crespo del Granado, P.; Egging, R. Local electricity market designs for peer-to-peer trading: The role of battery flexibility. *Appl. Energy* **2018**, *229*, 1233–1243. [CrossRef]