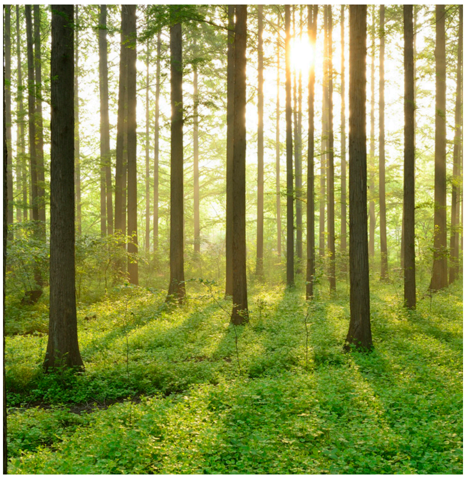
BLOCKCHAIN FOR SMART GRID OPERATIONS, CONTROL, AND MANAGEMENT

REPORT 2022:888



ELNÄTENS DIGITALISERING
OCH IT-SÄKERHET

Energiforsk

Blockchain for Smart Grid Operations, Control and Management

JIANGUO DING
YOHANNES TADESSE AKLILU

ISBN 978-91-7673-888-7 | © Energiforsk September 2022
Energiforsk AB | Phone: 08-677 25 30 | E-mail: kontakt@energiforsk.se | www.energiforsk.se

Förord

Projektet *Blockchain based Production and Distribution Controls of Smart Grids* tillhör programmet *Elnätens digitalisering och IT-säkerhet* och syftar till att utveckla blockkedjebaserade lösningar för att tillhandahålla en säker, pålitlig och effektiv tillämpning av ny småskalig elproduktion och eldistribution som kan integreras till regionalt eller nationellt elnät.

Delningsplattformar för modern elproduktion, eldistribution och förbrukning är behövs för att styra och övervaka integrationen och automationsprocessen. Utmaningarna gäller skydd av mikronätsystem under drift, kraftbalansering och kommunikation mellan olika distribuerade generatorer. Därför behövs vetenskapliga metoder för att säkerställa automatisering av infrastrukturen och decentraliserade tillämpningar av elproduktionen och eldistributionen.

Projektdeltagare i projektet har varit Jianguo Ding (projektledare) och Yohannes Tadesse Aklilu från Skövde Universitet.

Energiforsk tackar referensgruppen för deras stöd och uppföljning av projektet. Referensgruppens ledamöter var Harald Klomp från Vattenfall Eldistribution, Mathias Mellberg från Skövde Energi och Simon Lundqvist från Power Circle.

Stort tack också till programstyrelsen för programmet som består av ledamöterna:

- Kristina Nilsson, Ellevio (ordförande)
- Arne Berlin, Vattenfall Eldistribution
- Hampus Bergquist, Svenska kraftnät
- Ferruccio Vuinovich, Göteborg Energi
- Teddy Hjelm/Per-Olov Lundqvist, Gävle Energi (Elinorr)
- Torbjörn Solver, Mälarenergi (vice ordförande)
- Magnus Sjunnesson, Öresundskraft
- Adam Nilsson/Thorsten Handler, Jämtkraft
- Magnus Brodin, Skellefteå Kraft
- Johan Örnberg, Umeå Energi Elnät
- Peter Ols, Tekniska Verken i Linköping
- Jesper Bjärvall, Karlskoga Energi
- Peter Addicksson, HEM
- Malin Wallenberg, VB Energi
- Claes Wedén, HitachiEnergy Sweden
- Katarina Porath, ABB
- Björn Ållebrand, Trafikverket
- Patrik Björnström, Sveriges Ingenjörer (Miljöfonden)
- Matz Tapper, Energiföretagen Sverige (adjungerad)

Energiforsk framför ett stort tack för värdefulla insatser till samtliga intressenter:

Ellevio
Vattenfall Eldistribution
Svenska kraftnät
Göteborg Energi
Mälarenergi Elnät
Öresundskraft Elnät
Tekniska Verken i Linköping
Skellefteå Kraft Elnät
Umeå Energi Elnät
Jämtkraft Elnät
Elinorr ekonomisk förening
Eskilstuna Strängnäs Energi&Miljö
Karlstads El- och Stadsnät
Borås Elnät
Halmstad Energi&Miljö Nät
Luleå Energi Elnät
Hitachi ABB Power Grids
ABB
Trafikverket
Sveriges ingenjörer (MF)
Forumet Swedish Smartgrid
Teknikföretagen
Exeri
Evado
Huawei Sverige
Borlänge Energi
Nacka Energi
Västerbergslagens Elnät
PiteEnergi
Södra Hallands Kraftförening
Karlskoga Elnät
Bergs Tingslags Elektriska
Härjeåns Nät
Sandviken Energi Nät
Sundsvall Elnät
Dala Energi Elnät
Elektra Nät
Gävle Energi
Hamra Besparingsskog
Hofors Elverk
Härnösand Elnät
Ljusdal Elnät
Malungs Elnät
Söderhamn Elnät
Åsele Elnät
Årsunda Kraft& Belysn.förening
Övik Energi Nät

Stockholm i augusti 2022
Susanne Stjernfeldt

Summary

Power generation, distribution, transmission, and consumption face ongoing challenges such as smart grid management, control, and operation, resulting from high energy demand, diversity of energy sources, and environmental or regulatory issues. To better optimize and control the renewable energy system and its integration with traditional grid systems and other energy systems, corresponding technologies are needed to meet its growing practical application requirements: decentralized management and control, support for decentralized decision-making, fine-grained and timely data sharing, maintain data and business privacy, support fast and low-cost electricity market transactions, and maintain the security and reliability of system operation data, and prevent malicious cyberattacks. Blockchain is based on core technologies such as distributed ledgers, asymmetric encryption, consensus mechanisms, and smart contracts and has some excellent features such as decentralization, openness, independence, security, and anonymity. These characteristics partially meet the technical requirements of future renewable energy systems.

This report provides a comprehensive overview of blockchain-based smart grid management, control, and operation solutions. The report compares with related reviews and highlights the challenges in management, control, and operation for a blockchain-based smart grid, as well as future research directions in five categories: collaboration between actors, data analytics and management, control of network imbalances, decentralization of network management and operation, security and privacy.

The report reviews how blockchain technology can potentially solve the challenges of decentralized solutions for future renewable energy systems. As a result, several applications of blockchain for renewable energy are discussed, such as electric vehicles, decentralized P2P energy transactions, carbon certification and trading, physical information security, energy transfer, Energy-to-X, and the Internet of Energy.

A guideline for the implementation of blockchain to corresponding applications for future renewable energy is also presented in this report. This includes the different blockchain system architectures, the data flow from the power grid processed and recorded, the choice of the appropriate consensus, and the different blockchain frameworks.

These are the results and conclusions of a project, which is part of a research programme run by Energiforsk. The author/authors are responsible for the content.

Keywords

Smart grid; blockchain; smart grid management; smart grid control and operation renewable energy, decentralized framework, decentralized management

Sammanfattning

El produktion, distribution, överföring och förbrukning står inför pågående utmaningar som smart näthantering, kontroll och drift, som är ett resultat av hög energiefterfrågan, mångfald av energikällor och miljö- eller regelfrågor. För att bättre optimera och kontrollera det förnybara energisystemet och dess integration med traditionella nätsystem och andra energisystem, behövs motsvarande teknik för att möta dess växande praktiska tillämpningskrav: decentraliserad förvaltning och kontroll, stöd för decentraliserat beslutsfattande, finkornigt och aktuellt datadelning, upprätthålla data och affärsintegritet, stödja snabba och billiga elmarknadstransaktioner och upprätthålla säkerheten och tillförlitligheten för systemdriftsdata och förhindra skadliga cyberattacker. Blockkedja är baserad på kärnteknologier som distribuerade reskontra, asymmetrisk kryptering, konsensusmekanismer och smarta kontrakt och har några utmärkta funktioner som decentralisering, öppenhet, oberoende, säkerhet och anonymitet. Dessa egenskaper ska delvis uppfylla de tekniska kraven för framtida förnybara energisystem.

Den här rapporten ger en omfattande översikt över blockkedjebaserade lösningar för smart näthantering, kontroll och drift. Rapporten jämför med relaterade recensioner och belyser utmaningarna inom förvaltning, kontroll och drift för ett blockkedjebaserat smart nät, såväl som framtida forskningsriktningar inom fem kategorier: samarbete mellan aktörer, dataanalys och hantering, kontroll av nätobalanser, decentralisering av nätförvaltning och drift, säkerhet och integritet.

Rapporten går igenom hur blockkedjeteknik potentiellt kan lösa utmaningarna med decentraliserade lösningar för framtida förnybara energisystem. Som ett resultat diskuteras flera tillämpningar av blockkedja för förnybar energi såsom elektriska fordon, decentraliserade P2P-energitransaktioner, certifiering och handel med koldioxidutsläpp, fysisk informationssäkerhet, energiöverföring, Energi-to-X och Internet för Energi.

En riktlinje för implementering av blockkedja till motsvarande tillämpningar för framtida förnybar energi presenteras också i denna rapport. Detta inkluderar olika blockkedja -systemarkitektur, dataflöde från elnätet bearbetas och registreras, val av lämplig konsensus samt de olika blockkedja -ramverken.

List of content

1 Introduction

1.1 BACKGROUND AND MOTIVATION

With more and more applications and technological advances, IoT and other power-operated devices are rising. Numerous small- and large-scale power generation and distribution solutions have been tested worldwide to meet the energy demand. In addition, the demand for sustainable and renewable energy in all sectors of society is forcing power generation to be versatile. Three fundamental principles also drive the requirements for a future energy system: Decarbonization, Decentralization, and Digitalization (Andoni, et al, 2019) that ultimately provide the framework for the European Commission's Energy Union Package (European Commission (EU)), 2015). Renewable energy continues to grow in the energy market and will dominate the energy landscape in the future. The E.U.'s overall energy demands had to reach at least 20% by 2020, and the Nordic targets were higher: 30% for Denmark, 38% for Finland, 72% for Iceland, 67.5% for Norway, and 49% for Sweden.

Nevertheless, all Nordic countries met or exceeded their targets two years earlier. These results are due to the flexibility of electricity markets in the region, the favorable starting position in the energy mix in sustainable power to others, and the increased demand for carbon-free energy, heating, and transportation. Nordic energy consumption is about 100 million tonnes (Mtoe), with a low of 96.6 Mtoe in 2009 and a high of 104.2 Mtoe the following year after the global financial crisis (Leander, 2021, Tveten, 2020).

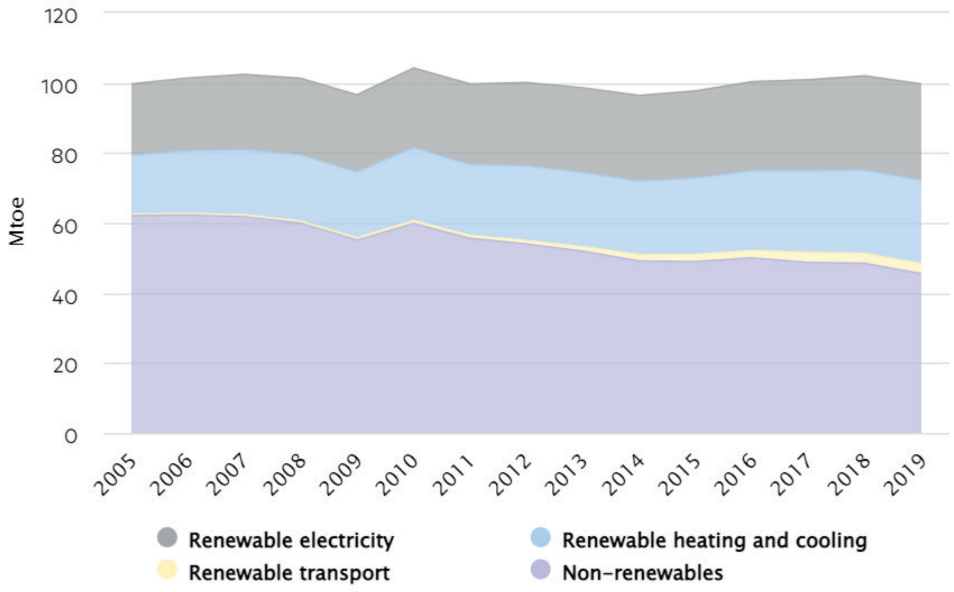


Figure 1. Energy consumption in the Nordic countries (Leander, 2021, Tveten, 2020)

Figure 1 shows the trend of energy consumption in the Nordic countries. Governments worldwide have set official policy or legislation targets to increase installed renewable energy capacity by 2030. To meet these targets, about 721 gigawatts of wind, solar, biomass, waste-to-energy, geothermal, and marine power plants would need to be built over the next decade (Ajadi, et al. 2020). Therefore, the growth trend of renewable energy is a sign that renewable energy will play an important role in the future energy landscape and will profoundly impact the development of society as a whole. But developing and using renewable energy efficiently is an urgent issue nowadays.

The emergence of low-voltage power generation and distribution systems leads to the concept of the Internet of Energy (IoE) (Shahzad, et al, 2020). The development of IoE has several advantages. It promotes energy generation, distribution, and consumption while meeting the energy demand via smart and automated tools that ensure secure data exchange among stakeholders (Mollah, et al., 2020). The IoE is designed as an open network, which means that all energy sources are equally important (Wang & Su, 2020).

According to the system model proposed by the National Institute of Standards and Technology (NIST) (Pillitteri & Brewer, 2014), a smart grid is a higher-level grouping of organizations, buildings, people, systems, devices, or other actors that share similar goals to exchange, store, process, and handle information needed in the smart grid. The smart grid domains include generation, transmission, distribution, consumption, operation, service provider, and market. An overview of the interaction between the different smart grid domains is shown in Figure 2 (Pillitteri & Brewer, 2014). The generation domain is responsible for energy production using various resources. The service providers control the energy flow and are responsible for energy distribution, operation, and trading. Customers refer to the various Advanced Metering Infrastructures (AMI), automation stations, demand response, smart appliances, sensors, smart objects, supervisory control and data acquisition (SCADA), electric vehicles, and home energy management (El Mrabet, et.al, 2018).

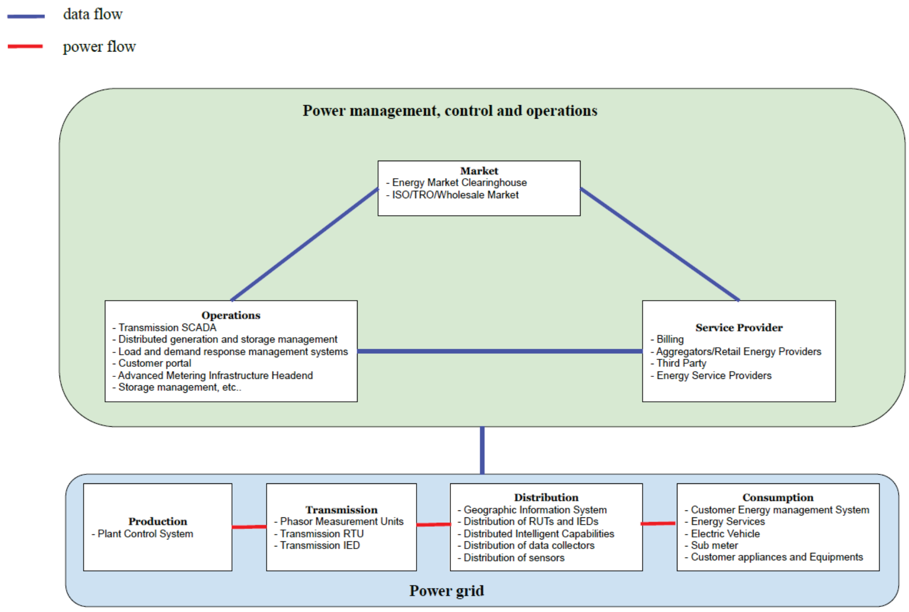


Figure 2. An overview of stakeholders in the different smart grid domains

The AMI collects, measures, and analyzes energy consumption by enabling bidirectional communication between the utility and the consumer. It consists of three main components: smart meters, the AMI center, and the communication network. Smart meters record and monitor electricity consumption and transmit real-time data to the AMI center. The AMI center is a server responsible for data management systems. Various communication protocols are used between the household appliances, smart meters, and the AMI center (Faisal, et.al., 2014).

The SCADA system operates energy systems by measuring, controlling, and monitoring the power grid. The main features of the smart power grid are real-time control, operational efficiency, increased grid stability, seamless integration with new distributed database technologies, and renewable energy systems. Smart grids can also be divided into locally managed microgrid infrastructures that deliver emission-free energy and are less dependent on centralized energy sources and high-voltage governmental or corporate-based power units.

Six main requirements have been identified for the smart grid to become intelligent (Ourahou, et.al., 2020): (1) control of consumer information that enables consumers to have reliable and frequent information about their electricity consumption, (2) accommodation and production technologies that enable a balance between supply and demand, (3) an economic exchange market that enables local market prices and promotes local microgrid production, (4) prospect of quality energy by diagnosing voltage fluctuations, (5) technical and operational specifications that ensure operational optimization, and (6) security against vulnerabilities that ensure resistance to various types of attackers. The development and implementation of the smart grid have immensely improved the efficiency of management, control, and operation of the power grid and facilitated the integration of renewable energy sources, electric vehicles, bidirectional communication, automated and self-maintaining systems that involve consumers (Salkuti, 2020).

The current trend toward developing and expanding microgrids makes centrally controlled intelligent grid management, control, and operation obsolete and difficult to implement. Fossil-free energy generation and distribution vary depending on weather, energy sources, geographic locations, existing infrastructure, and energy demand, among other factors. These variations and the decentralization of the energy system require modern and flexible management and operation systems and innovative energy storage systems (Mattila, et.al., 2016). It is also important to understand how to balance power generation and distribution in line with demand across seasons. The length of power lines accounts for a large portion of energy losses. Microgrid and renewable infrastructure generation and distribution can drastically minimize this energy loss while protecting the environment (Konashevych, 2016). The introduction of the electricity market can be a motivating factor for the expansion of microgrid production, as it could increase the generator's revenue while minimizing its consumption costs (Xue, et. al., 2017). The challenge is establishing coordinated and systematically automated production and distribution controls of these microgrids as the number of prosumers increases. The available technologies and achievements of the energy sector are not suitable for microgrids and therefore many actors in the energy industry propose blockchain (Yuan & Wang, 2016) to manage power transactions in microgrids to promote local consumption of distributed generation, decentralize grid management, and P2P power trading (Xue, et. al., 2017).

Distributed renewable energy sources are in high demand to address the challenges of climate change while efficiently balancing energy production, distribution, transmission, and consumption. With a variety of alternative energy sources, most fuel-based devices can be electrified, minimizing long-distance transmission losses, carbon emissions, and pollution (Davis, et al., (2018); Mollah, et al., (2020). Today, small generators and energy storage systems are increasingly connected to the traditional electric grid. The most common energy sources have been fossil fuels and hydro-power, requiring significant investment at the state or corporate level. Technological advances in recent decades are opening windows of opportunities for low-voltage renewable electricity generation by private and small businesses. In Sweden, for example, there are a total of 65819 solar panels and 4333 wind turbines installed in the year 2020, representing an annual renewable energy generation increase of approximately 40% from 2016 (Energimyndigheten, 2020). These numbers are expected to grow rapidly in the coming years as the Swedish government plans to use 100% renewable energy by 2040. The generation and distribution of decentralized emission-free low-voltage energy are highly recommended and can complement the traditional power sources. The 2030 renewable energy targets that have already been incorporated into official policy by 87 governments worldwide aim to build an estimated 721 gigawatts of new capacity in wind, solar, and other non-hydro renewable energy technologies over the next decade (Ajadi, et al, 2020).

1.2 A BRIEF LITERATURE SURVEY

The coordination and integration of many energy sources could pose a challenge to highly regulated, traditional, and centralized energy systems. The transition to a decentralized architecture can modernize the energy management and operation as well as the control and monitoring of the integration and automation process, which are still lacking (Hannan, et al., 2020). Various research has highlighted the challenges in protecting microgrid systems during operation, power balancing, and communication between distributed generation (DG) units such as wind turbines, coal, photo-voltaic systems, biomass, hydropower, and fuel cells, etc. (Badal, et al., 2019). Therefore, it is desirable to integrate microgrid generation and distribution with conventional power grids to create a common and efficient data exchange mechanism.

With its decentralized and secure platform for information exchange as its main feature, Blockchain technology can be an interesting example of unifying information exchange among different actors. The application of blockchain in the energy sector is still in its infancy and has a short development history (Wang & Su, 2020). However, there has been a growing interest in some research reports, application scenarios, and project initiatives in recent years (Alladi, et al., (2019); Andoni, et al., (2019); Di Silvestre et al. (2020); Hamouda et al., (2020); Konashevych, (2016); Mattila, et. al. (2016); Mazzola et al., (2020); Hussain, et al. (2019); Li, et al. (2019); Foti & Vavalis (2021); Kappagantu & Daniel (2018); Musleh, et al. (2019); Mollah, et al., 2020). Some blockchain-based frameworks have also been proposed with particular focus on energy trading for microgrids (Xue, et. al., 2017) and distributed energy market for pricing (Cheng, et al., 2017). Ethereum-based energy trading using information transactions between smart meters in households and distribution system operators (DSOs) has also been proposed (Hussain, et al., 2019). In addition, wireless sensor networks (WSNs) and the Internet of Things (IoT) provide alternative solutions to privacy and security problems through efficient data aggregation and optimization of energy generation and consumption using smart systems that can monitor and interact with each other (Alladi, et al., (2019). The highly diversified energy sector needs a common platform for smart grid management, operation, and control. Proper communication between the different DG units that are connected to the main grid and proper connection contributes to better smart grid performance (Badal, et al., (2019); Galici, et al., (2021)). Communication between DG units is essential for monitoring the voltage and frequency of the microgrid.

2 Challenges of renewable energy, and smart grid control, management, and operation

Renewable energy shows a significant growth trend and will bring important changes to the current power grid and the future power industry and commerce. The production, transmission, distribution, cooperation, coordination, and renewable energy consumption are very different from traditional power systems. These differences are reflected in their extensiveness, dynamics, distribution, interactivity, and integration. However, these distributed and decentralized renewable energy systems present new challenges. The goal of this chapter is to provide a comprehensive and detailed analysis of the challenges the renewable energy sector faces, as well as challenges in the smart grid control, management, and operation.

2.1 CHALLENGES IN THE RENEWABLE ENERGY SECTOR

2.1.1 Systemic

A single individual factor does not cause these challenges but problems inherent in the entire system (Andoni et al., 2019, Zimmermann and Hoppe, 2018, Sinsel et al., 2020).

The state-controlled electricity market hinders the development of decentralized electricity systems because a distributed generation has encouraged many participants to become energy producers. Centralized management and control pose legal, administrative, and economic hurdles for developers. Therefore, technical, commercial, and trading mechanisms for off-grid and near-grid services need to be established to support IoE (Internet of Energy) development.

Management, control, and coordination among renewable energy system participants are complex and necessary. To identify violations and other regulatory issues, regulators increasingly require a large amount of information from E&R companies for evaluation. Gathering and cleaning up essential data is the brunt of modern technology and procedures. There is also a significant risk of data misuse, exposure of critical company data, and harm to the company. They can also be misused.

2.1.2 Quality

Power quality (PQ) is a very important aspect of distributed renewable generation systems because today's loads are more sensitive to PQ disturbances, and nonlinear loads are increasing in power distribution networks.

Power quality challenges include: (1) Voltage and frequency oscillations in the integrated grid are caused by the unpredictable behavior of renewables due to often changing weather conditions. (2) Harmonics associated with the DG systems originates from the electronic power inverters used to integrate the renewables and inject active power into the grid, as well as from locally connected nonlinear loads at the point of common coupling (PCC).

Although voltage quality improvement by the VSM (virtual synchronous machine) method has great potential for stabilizing DG plants, balancing, harmonic, and reactive power compensation functions are performed in addition to improving voltage and frequency stability. There is also a need to develop some advanced control techniques for grid-connected inverters to improve DGs' ability to handle grids and load-side disturbances, eliminating the need for additional custom power devices (CPDs) (Bajaj & Singh, 2020).

2.1.3 Technical

1) **Adequate Planning**: Without adequate planning, large-scale deployment of distributed power sources may result in unstable voltage distribution. The operational requirements of the entire power system will need to be redesigned to accommodate emerging technologies such as smart grids, renewable energy, energy storage, etc.
2) **Rapid demand response**: Demand response technologies require continuous, trusted access to the system via multiple communication technologies, which is not currently possible in many regions of the world.
3) **Decentralized operations**: Decentralized operations are needed to provide adequate support for independent providers and consumers.
4) **Accelerating the energy supply chain**: The efficient use of renewable energy depends on the ability to accelerate the process of energy production, storage, transmission, distribution, and consumption.
5) **Security**: The security of the commercial chain from production to consumption is not in place. This covers the security of energy networks, financial transactions, and all online information.
6) **Resilience**: An integrated and resilient renewable energy system will support cross-regional applications to adapt to dynamic energy markets. It is not possible to accurately calculate the total energy use in time. In turn, total consumption depends on hardware efficiency and climate disruption, depending on the region's availability of green or brown power.

2.1.4 Economic

These are areas of dynamic economic conditions captured by income or other standard economic indicators (Andoni et al., 2019, Zimmermann and Hoppe, 2018). Compared to centralized plants, the capital cost per kilowatt is generally higher for distributed electricity, mainly because of connection costs. Due to the high capital costs and longer life cycles, upgrading infrastructure to a more efficient transmission and distribution system is complex.

In addition to power distribution and transmission systems, integration with interconnected distributed generation resources is also considered for system stability reasons. Power transmission and transaction costs between distributed and small-scale generation and consumption are difficult to control.

2.1.5 Stability

The rotational inertia of variable renewable generators is significantly lower than synchronous generators. In the event of an imbalance between market forces, this leads to faster frequency fluctuations. Variable renewable generation is diverted or throttled when frequency fluctuations are too rapid (Hodge et al., 2020; Adetokun et al., 2020, Adetokun et al., 2020).

Due to the short-term fluctuations in renewable generation, there is a decrease in frequency regulation reserves. Variable renewable generation, on the other hand, does not provide any frequency reserves at all. Small variable renewable energy generators do not have remote control interfaces. As a result of the uncontrolled injection of fluctuating renewable generation, unpredictable power flows occur, resulting in shortened equipment life, trips, or equipment damage (Hodge et al., 2020; Tveten, 2020).

Because variable renewable generation is site-dependent, transmission distances between generation and consumption sites become more extended, resulting in increased transmission losses. Variable renewables must be shut down when they operate outside a certain voltage band. For this reason, variable renewable generators shut down more frequently as voltage fluctuations increase. A larger grid area also results in shorter equipment life and the possibility of damage (Alam, 2020; Tveten, 2020, Choudhury, 2020).

Interactions between renewable energy providers and the power grid are becoming more frequent, leading to unnoticed power fluctuations (Bajaj & Singh, 2020). A lack of control can lead to shortened asset life, outages, or faults. As a result, there is a lack of coordination in setting voltage trip limits. This results in variable renewable generators tripping more frequently as voltage fluctuations increase. These cascading trips result in violations of dynamic stability standards or increased stability events.

2.1.6 Imbalance

The stability of renewable energy sources is not sufficient. This has led to higher reserve requirements and a more erratic imbalance between generation and load. Activation, dispatch, or power curtailment must be balanced to maintain output.

Variable renewable generators have limited dispatch capability as their main resource supply shifts (Asija & Viral, 2021; Cole & Frazier, 2018). To compensate for unexpected outages of other power plants, variable renewable generators are limited. These unplanned mismatches between generation and load lead to accidental activation of balancers and control reserve systems. As renewable generation increases, the power requirements for conventional generation change, such as the need for a faster ramp-up. Therefore, generation-load imbalances, dispatch, or curtailment may occur in the short term (Cole & Frazier, 2018; Hodge et al., 2020; Tveten, 2020).

Because variable renewable generation is unpredictable, forecast accuracy decreases. Power activation, dispatch, or curtailment are the result of these unanticipated imbalances between generation and load (Asija & Viral, 2021; Bajaj & Singh, 2020, Impram et al., 2020). Insufficient long-term generation capacity As renewable generation increases, the performance criteria for conventional generation also change, such as nighttime or seasonal balancing of generation. These performance requirements must be met. Otherwise, long-term generation-load imbalances are foreseeable (Asija & Viral, 2021; Hodge et al., 2020).

2.2 CHALLENGES IN SMART GRID CONTROL, OPERATION, AND MANAGEMENT

The smart grid currently works with a centralized platform or intermediaries to provide services like billing, monitoring, bidding, and energy transmission. Although these solutions are mature and work properly, some of the challenges related to the current smart grid promote the integration of a large number of smart grids with renewable energy generators and Cyber-Physical Systems. The smart grid is also transforming into a decentralized topology with centralized management and interactive network using IoE (Internet of Energy) (Shahzad, et al, 2020). In this new IoE concept, each device is assigned certain attributes based on an identifier, geographic marker, address, bid price, and offer price based on its requirements. The introduction of these new technologies, along with the diversity and expansion of energy sources, complicates the energy sector's management, control, and operation. We discuss these challenges in detail based on five categories, see Figure 3.

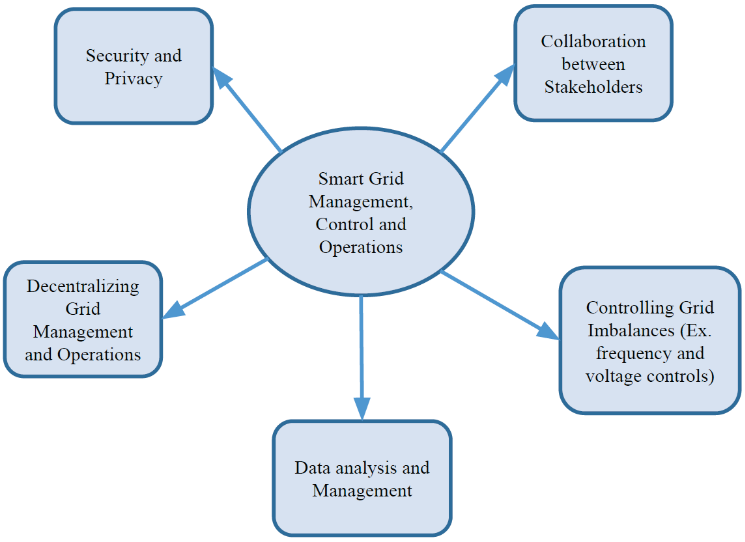


Figure 3. Challenges for management, control, and operation of smart grid.

2.2.1 Collaboration between Stakeholders

New technologies, high investments, lack of accurate information, etc., complicate the coordination between actors in the energy sector. The current smart grid system faces the problem of energy balancing, especially when different actors are involved in the generation, distribution, trading, and consumption processes. While much of the literature focuses on the technical aspects of the smart grid challenges, the collaboration between stakeholders is equally important and needs to be addressed appropriately (Kappagantu & Daniel, 2018). Energy suppliers and traders typically request estimated energy from generators based on their demand analysis. Such an estimate can be inaccurate due to several factors: Expansion of the region, population growth, environmental factors, and an increase in microgrid generators in the area. This can lead to high distribution losses, unbalanced voltage and frequency loads, and consequent power outages. In addition, some microgrids, such as solar systems, produce more energy during the warm summer months when energy demand is lowest. A modern data exchange system between the stakeholders could pave the way to store the excess produced energy in a local hydrogen gas or battery without affecting the main grid infrastructure. Therefore, it is important to establish close cooperation between relevant players such as generators, distributors, retailers, consumers, and regulators to facilitate grid management.

2.2.2 Controlling Grid Imbalance

Physical and technical problems can contribute to power generation and consumption imbalances. The failure of some network components, such as insulation faults or damaged cables, interference from third parties, vandalism, and natural causes such as wind or storms, can contribute to imbalances in power supply. Technical problems such as malicious attacks, frequency deviations, overloads, synchronization losses, and voltage dips can also contribute to power imbalances (Ourahou, et.al., 2020). Voltage deviations are another potential challenge to grid imbalances. For example, a PV power plant produces more energy during the sunny part of the day when demand is lower. This causes the PV power plant to produce more than the grid load capacity and causes Reverse Power Flow into the transmission grid, (Frost, et al. (2020); Unahalekhaka & Sripakarach, (2020); Mahato, et al., (2021); Holguin et al. (2020)). Therefore, controlling and monitoring the power supply in each period is essential. The article (Sun, et al., 2019) examined the emerging challenges for voltage control in the smart grid. All stakeholders must adjust their power generation, distribution, and consumption to regulate both active and reactive power (Ourahou, et.al., 2020). However, this becomes a challenge due to the number and diversity of power generation methods and regulatory requirements.

2.2.3 Data Analysis and Management

Current smart grid data management faces the problem of data aggregation quality, security, compliance control, common scope, and efficiency of the management mechanism (Liang, et al., 2020). A large amount of data is generated and transferred between different entities (Kappagantu & Daniel, 2018). Accurate and consistent incoming data streams such as weather forecasts and power generation status allows operators to control and monitor the grid system. Such information is crucial to avoid sudden and unexpected power supply disruptions. In addition, such big data can also be used for grid operations, alarms, demand forecasts, generation estimates, price adjustments, etc. The data collected tends to be quite large, as multiple smart grid domains are involved in the process. For example, an Advanced Metering Infrastructure that collects data every 10 minutes instead of every month could increase the data analysis process by more than 4000 times. There is also a regulatory requirement to provide accurate data as frequently as possible, which is challenging. Modern, automated, and secure data processing technology can improve the smart grid's data management, storage, and reporting.

2.2.4 Decentralizing Grid Management and Operation

Decentralizing grid operations allows stakeholders to control and manage their data locally. The control and operation of a smart grid in a decentralized environment is an important research topic. Research areas include demand-side control and optimized grid operation (Samad & Annaswamy, 2017). Distributed automation devices are used to decentralize the operation of the grid. These devices are phasor management units (PMUs), remote terminal units (RTUs), SCADA, and smart meters used to collect and monitor data. In (Salkuti, 2020), distributed automation approaches for electric power distribution systems, benefits, and challenges were studied. High-resolution sensors with the ability to report real-time conditions and improve the visibility of the distribution system operator beyond substation assets were also considered. In addition, there are challenges associated with the coordinated and cost-effective integration of distributed smart grid systems, generation assets, and demand response facilities. This complicates the management and operation of distributed energy resources. Further work is needed to facilitate coordination between decentralized and centralized stakeholders.

2.2.5 Security and Privacy

While decentralizing the operation and management of the smart grid has many benefits, it also brings security and privacy challenges. The SCADA module in modern power systems collects data at remote terminals and transmits and stores it in plain text to the main control center. This centralized data collection and storage is highly vulnerable to cyberattacks. Cybersecurity is one of the current smart grid's biggest and most difficult challenges. Over the years, several cyberattacks have taken place on the smart grid (Kimani, et al., 2019). Attackers use the four steps of Exploration, Scanning, Exploitation, and Maintaining Access (Engebretson, 2013) to control the system. There are several known attacks on smart grids. One is the jabbing attack, in which the attacker installs a malicious smart power meter that sends false data, causing desynchronization and power interruption. The puppet attack sends a signal to the node. The attacker then controls the node and sends more signals into the network, causing the smart meter network to become unstable.

Another example is the stack smashing attack, which compromises the application layer of the network and leads to the disclosure of sensitive data. An experimental attack, on the other hand, makes the smart grid layer vulnerable to DoS attacks (Kumar, et al., 2019). A comprehensive discussion of attack mechanisms, detection, and countermeasures can be found in (El Mrabet, et al., 2018).

Security is, therefore, a major challenge in the management, control, and operation of smart grids. Given the alarming increase in IoT devices with limited security capabilities connected to the smart grid system, much needs to be done to protect sensitive personal and corporate data as well as national security (Kimani, et al., 2019).

Several technical and operational changes can be identified in summarizing the challenges of smart grid management, control, and operation. The dynamic generation and distribution of energy by many distributed generators, the digitization of the grid, and advanced metering systems contribute to fault-tolerant transmission and distribution control. Smart grid owners often have dual roles (generator and consumer), and loads become dynamic and more interactive (Foti & Vavalis, 2021). Centralized and traditional grid management and operation face challenges, and utilities seek viable solutions to these problems. Although distributed energy systems offer benefits such as user tracking, cost savings, and optimized resource allocation (Wang & Su, 2020), technological immaturity and incentive mechanisms compromise the core interests of stakeholders. Table 1 summarizes smart grid management, control, and operation challenges.

Table 1. Challenges to the current and future smart grids.

Challenges	Description	Ref.
Collaboration between stakeholders	– Difficulty in allocating resources – Difficulty in establishing reliable data exchange for common goals – Operational challenges due to the dynamics of renewable energy generation – Problems in developing an up-to-date supply and demand program – Limited role or influence of microgrid generators on the management and operation of the smart grid – Problems with real-time performance – High transaction costs – Large energy companies may dominate microgrid generators' voices – Difficulty in getting prosumers to participate in decentralized smart grid management. – Overcoming regulatory challenges – Transparency – Accountability	(Kappagantu & Daniel, (2018); Galici, et al., (2021))
Controlling grid imbalances	– Need to monitor smart grid sensors and AMI to control grid overloads and power outages. – The problem of overloading the grid – Load balancing in the grid – Can create Reverse Power Flow – Control of voltage and frequency – Automatic fault detection and maintenance	(Ourahou, et.al., (2020); Sun, et al., (2019); Frost, et al. (2020); Unahalekhaka, & Sripakarach, (2020); Mahato, et al., (2021); Holguin, et al. (2020))
Data analysis and management	– Analyzing the quality of produced energy – Large scale and complex data aggregation and deployment – Data management on energy production, distribution, and consumption – Management of data transactions between all prosumers	(Kappagantu & Daniel (2018); Liang, et al., (2020))
Decentralizing Gird management and operations	– Development of a decentralized energy management – Automated P2P energy trading – Automated grid monitoring – Increase in the complexity of energy generation and distribution – The flexibility of energy generation and distribution – Difficulty of scalability – Traceable energy management	(Salkuti, (2020); Triantafyllou, et al., (2020); Samad & Annaswamy, (2017))
Security and privacy	– Tamper-proof system for protecting customer data recorded and transmitted in the smart grid – Access control – Authentication – Secure data storage – Security and data protection for smart grids – Data protection and compliance – Establishing secure communications – Protecting the smart grid from cyber attacks – Implementing a decentralized and secure authentication mechanism – Data privacy	(El Mrabet, etal, (2018); Kimani, et al., (2019); Engebretson, (2013); Kappagantu & Daniel (2018))

3 Blockchain technology

While this technology has been around since the 1990s, it has attracted great interest since Nakomoto published a paper titled Bitcoin: A Peer-to-Peer Electronic Cash System (Nakamoto, 2008). The paper describes a peer-to-peer electronic transaction between two parties (sender and receiver) without an intermediary financial institution. Since then, the technology has been used for electronic money transactions as well as various other non-financial areas. E-commerce systems such as Bitcoin, Ethereum, Ripple, and Litcoin are some popular blockchain applications that are expanding to the financial market and attracting millions of users (Yaga, et al., 2019).

The exact definition of blockchain technology differs depending on the desired function and specific implementation. It uses cryptography, distributed ledgers, and consensus, among others. However, it is important to emphasize that not all systems with cryptographic implementations can be associated with Blockchain and not all distributed ledgers can necessarily be used for the cryptographic functions associated with Blockchain (Mattila, 2016). Blockchain is a collection of fault-tolerant consensus algorithms, smart contracts, public-key cryptography, peer-to-peer networks, and database management technologies that together form a low-cost, secure, and efficient operational management system (Li, et al., 2019b). Each block is encrypted and linked to the previous one after validating and consensus decision processes. There is no limit to the number of blocks in the chain, making it harder to invalidate older blocks. Anyone on the network can view or modify the data without a centralized institution responsible for recording the activity. Blockchain technology is commonly used for 1) a specific cryptographically patched and continuously growing timestamped database, 2) the distributed digital consensus architectures that the database enables, and 3) the application domains that build on that architecture (Mattila, 2016).

A typical blockchain transaction can be divided into three phases. 1) The transaction request, where a node requests the creation of a block by sending data with a specific value to another node within the network. In this phase, a hash code is generated and distributed to all network nodes. 2) All nodes within the network verify the validity of this block based on a previously established consensus mechanism. 3) A node that makes a real effort and finds the correct hash value is awarded as the winner and is thus entitled to add the latest block to the chain.

A blockchain architecture consists of a chain of blocks connected by hash codes that not only serve as IDs but also ensure the integrity of the blocks (Fu, et al., 2021). Each block consists of a block header, which includes hash values of the previous block header, a timestamp, a nonce, and a hash of the Merkel tree containing a set of transactions in the block. Blockchain security is based on public-key cryptography, followed by hash functions for attack resistance, double spending prevention, and digital signatures for agreement approval and consensus.

Blockchain applications in the financial sector and beyond are being enhanced daily by several other technologies that have adopted the technology to save time and money. Industry and enterprise-level systems are implementing blockchain to make their existing system more efficient by minimizing centralized mediation of data transactions and controls (Mattila, 2016). Retailers like Walmart and Maersk use blockchain to track everything from food production to packaging, shipping, distribution, and sales (Rapier, 2017). That is, instead of the manufacturer, the shipper, and other stakeholders collecting their records of the product, blockchain could allow all parties to follow up on every step in a secure ledger.

3.1 BLOCKCHAIN FEATURES

Blockchain has good characteristics (Tschorsch & Scheuermann, (2016); Mollah, et al., 2020; Fu, et al., (2021)).

1) **Decentralization**: the blockchain is managed by various decentralized nodes through a consensus protocol and operates on a peer-to-peer basis without needing authorized and centralized trusted nodes.

2) **Scalability**: as more and more nodes join the network, the blockchain network can be expanded at will.

3) **Untrusted but secure**: In a blockchain, it is not necessary to blindly trust certain entities. The exchange of information between nodes in the blockchain system follows a predetermined procedure to prevent the identity of either party from being revealed. Nodes do not rely on trusted intermediaries for communication and all records/transactions are protected by asymmetric cryptography. The blockchain does not require blind trust in specific entities. Procedural standards are used in the blockchain to establish mutual trust. Nodes do not rely on a trusted intermediary for communication, and all records/transactions are protected using the principle of asymmetric encryption. Strong protocol algorithms protect the enforceability of blockchain data, non-destructive changes, and outside attacks. For example, the Bitcoin blockchain can only be achieved if 51% of the computing power is controlled. Therefore, data manipulation costs are much higher than the potential benefits. Therefore, it is unlikely that participants will attempt to manipulate data to improve blockchain data security.

4) **Immutability**: as long as most nodes are not malicious, the content of the block cannot be changed. Each networked node in the blockchain has the same status in the system. All nodes in the system will save the created data block. Therefore, all nodes capture and store the transaction data, and the database is more robust.

5) **Openness, transparency, and verifiability**: the blockchain system uses trusted algorithms with open and transparent operating rules to govern transaction behavior. Data exchange between system nodes does not require trust. All data is available to all participants, and nodes are encrypted in the system, except for confidential information. The network nodes can verify the records' authenticity and ensure that the blocks are not modified. By opening all records to anyone, transparency allows these blocks to be verified by any node on the network. Anyone can query the blockchain information using the hash

value of the block header. To update information, each node must authenticate each other, so the information of the whole system is very transparent, and a node cannot mislead other nodes. As more nodes join the network, the blockchain network can spread freely. Network nodes can verify the authenticity of records to ensure that the block is not altered. By opening all records to all users, transparency allows these blocks to be verified by any node in the network. Therefore, the entire transmission process of the transaction object can be fully tracked and recorded, making it easier to monitor the transaction.

6) **Resilience**: any failure or malicious activity can be easily detected and recovered. This flexibility comes from the decentralization of the architecture, avoiding a single point of failure. All nodes store their entire chain on their premises. Blockchain technology is particularly promising in industries where peer-to-peer networks (such as grid-connected power generators and consumer networks) rely on shared data sets. All nodes store their entire chain on their premises.

7) **Automated contract execution**: smart contracts can be created on the blockchain, specifying the obligations of each participant and the terms and conditions for execution. Blockchain technology automatically evaluates the contract terms. When it is determined that all contract requirements are met, the blockchain technology automatically fulfills the contract terms. Smart contracts improve the efficiency of contract execution and are critically executed without robust third-party monitoring.

These features make blockchain a modern distributed network protocol that enables relationships between different participants who do not know each other. The technology is particularly promising in industries where peer networks, such as grid-connected power generators and consumer networks, rely on shared data sets. The power distribution system can also use blockchain to remotely control the power flowing into a given area by monitoring production and consumption statistics.

3.2 TYPES OF BLOCKCHAIN

Different classifications of blockchain can be found in literature based on access and validation rights, application environments, docking types, and application range (Wang & Su, 2020). Based on access and management rights, blockchain can be divided into permissionless and permissioned.

3.2.1 Permissionless Blockchain

In the permissionless (or public) blockchain, anyone can join or leave the network at will (Cash & Bassiouni, 2018), and any node can participate in transactions as well as consensus processes (Andoni, et al, 2019). In this system, the number of nodes is often large, anonymous, and untrusted. Cryptographic puzzles govern thrust and collaboration between users in the public blockchain. Systems such as Bitcoin and Ethereum are some examples of public blockchains (Nakamoto, (2008); Wood, (2017)). Some use cases are digital identities, voting, fundraising, etc.

Permissionless blockchain has attracted a lot of interest in the wake of Bitcoin (Nakamoto, 2008) and other digital currencies that sought to decentralize products and services without intermediary third parties. Because of its ability to store and exchange data irrevocably, industries such as retail and financial institutions have recognized the potential of this technology (Cash & Bassiouni, 2018). For example, if there is a blockchain with information describing a car's history from production to sale and subsequent services to use, people would prefer to rely on that information rather than the intermediary of the car. However, the system is quite slow. It is difficult to generate items of value. Security depends on the integrity of users. It is too transparent to keep sensitive data. Access is difficult to control. It is vulnerable to hacking and tampering. It consumes a lot of energy, and it is quite complex. Due to these limitations, consent-free blockchain is unsuitable for regulatory communication and smart grid management (Li, et al., 2019b).

3.2.2 Permissioned blockchain

Permissioned Blockchain is designed so that only authorized participants can access the ledgers. Anyone can join the network, but the consensus algorithm is run by a group of nodes that perform the necessary validation. With permissioned blockchain, no incentives are required. Users can determine the level of privacy, decentralization, and management. This system may be suitable for organizations such as the public sector and financial institutions that have a large volume of sensitive data and a number of supporting regulations. For example, a permissioned blockchain can be set up between organizations where certain counterparties can record transactions in the distributed ledger, but not everyone can read what is written in the ledger (Cash & Bassiouni, 2018). This can provide resilience and redundancy in data storage. The system is typically fast, highly customizable, energy-efficient, more flexible, and can be easily adapted to meet current regulations. However, these advantages come at the cost of immunity and censorship. They are also centralized, less transparent, and less anonymous (Andoni, et al. 2019). Furthermore, permissioned blockchains can be divided into private and consortial blockchains based on the levels of node access and validation, respectively.

Private Blockchain: is designed so that only authorized participants can access the ledgers. All data in the private blockchain is approved centrally by a specially authorized group, which also sets the access rights in the system. Private Blockchain does not need to be transparent, as data access is limited only to authorized nodes. The system is typically fast, highly customizable, energy-efficient, more flexible, and can be easily adapted to meet applicable regulations. An example of a private blockchain is MultiChain. Private Blockchain is a closed storage network that could limit the free expansion of local renewable energy and is not entirely suitable for smart grid management.

Consortium Blockchain: there is a need to integrate the features of public and private systems to create a more adaptable platform. The consortium blockchain features open consensus for public systems and centralized control for private systems. It is typically used by companies that want to develop their system and create a broad-based platform for sharing data with stakeholders. For example, consortium blockchain has been used to present marketing products in the banking sector (Dib, et al., 2018) and to distribute data between multiple stakeholders (Bamakan, et al., 2020). A multicentric blockchain system is suitable to participate in the regulatory process of a virtual power plant (Li, et al., 2019b). An example of such a system is the Hyperledger project, which has developed cross-industry blockchain frameworks (Casino, et al., 2019). Compared to the public blockchain, the consortium blockchain is less decentralized, does not focus on cryptocurrencies, and does not offer direct financial incentives to validators. The key features of these blockchain taxonomies are summarized in Table 2.

Table 2. Different features of blockchain classifications.

Taxonomies	**Permissionless**	**Permissioned**	
Properties	**Public**	**Private**	**Consortium**
Governance	Public - any node can join	Managed by one administrator	Managed by a set of participants
Access right	Any node can read, write, leave and join	Only authorized node	Only a set of authorized nodes
Network scalability	High	Low	Medium
Decentralization level	Highly decentralized	Highly centralized	Semi centralized
Protocol efficiency	Less efficient	Highly efficient	Highly efficient
Examples	Bitcoin, Ethereum, Ripple, etc	MultiChain	Hyperledger
Consensus algorithms	No permission is required (PoW: Proof of Work, PoS: Proof of Stake, PoET: Proof of Elapsed Time, etc.)	Permission required (PBFT: Practical Byzantine Fault Tolerance, PoA: Proof of Authority, PoI: Proof of Importance, etc.)	
Data Immutability	Highly immutable	Less immutable	
Transaction Validation	Incentive-based mining by any node	– List of authorized validators – No incentive required	
Main features	– Resistance to censorship – Unregulated and transnational – Anonymous identities – Scalable – Untrusted organizations can participate – Slow transaction speed	– Suitable for highly regulated companies – Efficient transaction throughput – Transaction without fees – Better protection against external attacks – Fast transaction speed	

3.3 SMART CONTRACTS

A smart contract is a self-enforcing computerized transaction protocol that contains the terms of an agreement between the parties involved (Szabo, 1997). It is designed to perform automatically, control, and document services according to the terms of the agreement. It performs transactions that meet the terms of the agreement between anonymous parties, comply with the organization's laws, or generate tokens (Clack et al., 2016) without involving an intermediary. Blockchain smart contracts' important feature makes transactions traceable, transparent, and irreversible. Smart contracts on the blockchain include agreements between multiple users to store and execute data (Wang & Su, 2020).

3.4 CONSENSUS ALGORITHMS

The consensus algorithm plays an essential role in maintaining the security and efficiency of the blockchain (Mingxiao, et al., 2017) especially in solving the

Byzantine General Problem (Lamport, et al., (2019); Castro & Liskov, (1999)), as well as in ensuring data consistency in case of errors (Fu, et al., 2021). Two types of fault tolerance can be found in the literature. The first involves fail-stop (or crash) faults that cause nodes to stop participating in the consensus agreement (Baliga, 2017). Such faults are usually caused by hardware or software failures and do not exhibit other malicious behaviors (Fu, et al., 2021), and are usually relatively easy to resolve. The second group is Byzantine faults which provide misleading information mainly due to bugs or attacks and usually behave pretty randomly. Several consensus algorithms can be found in the literature with particular characteristics and advantages and disadvantages (Ferdous, et al., (2021); Baliga (2017); Bamakan, et al., (2020); Fu, et al., (2021)).

For a blockchain system, the consensus protocol is crucial. The rule governs the creation of new valid blocks and a consistent blockchain leader. Different consensus mechanisms, including Proof of Work (PoW), Proof of Stake (PoS), Delegated Proof of Stake (DPoS), and Practical Byzantine Fault Tolerance (PBFT), are deployed in various blockchain applications. The primary and most used protocols include PoW and PoS. Several other consensus protocols are offered, such as Proof of Elapsed Time (PoET), Proof of Burn (PoB), Proof of Authority (PoA), Proof of Authority (PoA), and Proof of Capacity (PoC), etc. The consensus protocol defines a voting system to select the next accountant. In PoW, nodes (e.g., miners) compete with each other to solve hash puzzles and the first to have a solution can create a new block and propagate it across the network. PoS requires nodes to lock specific pills into the network rather than having a puzzle-solving competition to select the bookkeeper (Knirsch et al., 2020). A node's share affects its probability of being selected to verify transactions and create a new block. The verifier can only collect its coins and a payout, which precludes data forgery if the network recognizes the block.

The consensus protocol defines the key performance characteristics of a blockchain. The use of PoW in Bitcoin's consensus protocol has been widely criticized (a 51% attack means that the miner controlling over 51% of network computations can create blocks with fake transactions and invalidate blocks from honest miners). In terms of speeding up transactions and conserving resources, on the other hand, PoS is more powerful than PoW.

Although a significant number of transactions are performed with Bitcoin, the data processing rate in a blockchain is estimated to be about seven per second. In contrast, Ethereum averages up to 15 transactions per second. These low processing rates are mainly related to the consensus mechanism (PoW) used in Bitcoin technology. Nodes need to compute the PoW algorithm to add a block to the blockchain, which requires a lot of computing power and time. According to (Mollah et al. 2021), 30 billion kWh of electricity was consumed to process thirty million transactions, which is about 0.13% of the world's energy consumption. In the energy sector, the volume of transactions per second is particularly high for large-scale operations, as thousands of customers participate simultaneously in the process of energy procurement and distribution. Thus, the nodes in the consensus and validation process represent a large overhead. To solve this problem, the PoW algorithm could be replaced by the PoS or PoA algorithm. These algorithms require far less computing power and support higher transaction rates. The energy sector, with transaction speeds of several thousand per second, is exclusively served by another blockchain platform called EnergyWeb blockchain. It uses the consensus PoA mechanism, which makes processing so fast.

The impact of a consensus protocol on blockchain performance and the requirements for the consensus protocol are summarized as follows: 1) It should be energy efficient, as the primary goal is to promote sustainability. 2) PoW consensus protocols should be avoided. The system can provide a transaction platform to process a certain number of requests within an acceptable time period. 3) The consensus protocol establishes criteria for performance, latency, and scalability. 4) Security is an important consideration because many people and personal data are involved.

3.5 EVOLUTIONS OF BLOCKCHAIN

Blockchain development and innovations can be divided into three phases. Blockchain 1.0 concerns Bitcoin and other cryptocurrencies in both centralized and decentralized environments. Blockchain 2.0 explores various applications of the technology in non-digital currency scenarios such as smart contracts and smart cities like Ethereum. Blockchain 3.0 focuses on the underlying technology and provides a platform for trading applications and innovation for broader public service. For example, DAG (Directed Acyclic Graph) is typically placed in the third category.

4 Blockchain applications for energy sectors

The smart grid operations are traditionally controlled and managed centrally, making the grid infrastructure vulnerable to different kinds of attacks. This results in various operational delays due to extensive data management, access control, and security. This chapter reviews several potential blockchain applications for the energy sector.

Companies with large financial resources have traditionally generated, distributed, and controlled energy. The traditional power grid structure, the framework for electricity trading, and the management system are largely centralized. The decentralized system is based on distributed production, electricity storage, and market desire (Talat et al., 2020). The centralized system relies on a third party (intermediary) to handle transactions between suppliers and consumers. In centralized energy trading systems, some vulnerabilities remain and affect consumer satisfaction because they can disrupt business (Khalid et al., 2020). Increasing renewable energy technology and the market will change the energy landscape and require new technical solutions to manage the non-centralized renewable energy system (Ding & Naserinia, 2022).

1) **Distributed generation**: known as embedded generation, on-site generation, scattered generation, and decentralization, is the essential component of a decentralized energy system. The decentralized generation of heat and power is possible. However, heat cannot be transmitted over long distances and has always been generated locally. The shift to decentralized power generation makes it possible to coordinate heat and power generation in cogeneration plants. In this way, electricity and heat production boost the system's efficiency because heat is a by-product of many electricity generation processes.

2) **Electricity storage**: a fundamental constraint of electricity distribution is that electricity cannot be retained and generated on demand. Additional generation sources could create more problems in regulating supply to best meet demand in a decentralized system. Nevertheless, battery storage with compressed air, and pumped hydro-storage systems can help maintain the grid stability by storing energy when supply exceeds demand and feeding it back to the grid during peak periods. The storage of intermittent energy plants is especially useful, often generating at their highest capacity in the non-peak hours. Storage can be decentralized to enhance efficiency and generation. It can be off-grid or grid-tied.

3) **Demand response**: demand-response systems provide another option for managing grid stability if decentralized generation is connected to the grid. Grid management has traditionally concentrated on supply management. But emerging technologies, such as the smart grid and smart meters, enable power suppliers and users to monitor and communicate in real-time to improve system utilization. Many electricity users will sometimes be energy producers with distributed generation and storage.

In order to construct a decentralized energy system, smart grid technology is needed to facilitate grid management.

4) **Electricity industry**: a decentralized energy system is a relatively recent strategy in many countries. The power sector has traditionally concentrated on developing large, centralized power plants and transferring generation loads to regional consumers through extensive transmission and distribution lines. Decentralized energy systems are aimed at bringing energy sources closer to end-users. End users are scattered across an area so that energy generation can reduce inefficiencies in transmission and distribution and the corresponding economic and environmental impacts in a similar decentralized fashion.

Decentralized blockchain technology is worth speculating on renewable energy. It offers numerous benefits such as cost savings, efficiency, and an efficient procedure (Rahmadika et al., 2019). From an industrial perspective, Blockchain offers various advantages, like flexibility, scalability, and security. Blockchain also offers energy suppliers an alternative for their neighbors to sell excess energy. Moreover, in a decentralized blockchain system, third-party services are no longer required.

Advanced Metering Infrastructures (AMI) enables bidirectional communication between generators, distributors, retailers, and consumers, making it possible to transform the traditional workforce into a smart grid. Smart systems such as Wireless Sensor Networks (WSNs), the Internet of Things (IoT), Virtual Power Plants (VPPs), and other intelligent control systems also enable optimization of power generation and consumption. These advanced technologies make the power grid system smarter, more efficient, and automated (Alladi, et al., 2019). Table 4 compares the advantages of a decentralized blockchain-based smart grid with centralized, traditional smart grid management. It shows that using blockchain for data management and control of the smart grid is beneficial to creating a diversified platform where relevant stakeholders have equal influence on the overall operation of the infrastructure.

Table 4. Comparison of management, control, and operation between traditional and blockchain-based smart grids (Rhydwan, et al., 2020).

Smart grid domains	Traditional smart grid	Blockchain-based smart grid
Production	– Largely non-renewable energy sources are involved – Often at a large scale from the central source	– All energy sources can use the platform – Microgrid prosumers can make a significant contribution to the renewable energy market
Transmission and Distribution	– Consumers can't get updates on energy consumption regularly – Limited control due to lack of demand-supply information flow – Long distribution distance contributes to high distribution loss – Power transaction procedures can be a bit complex and insecure	– Consumers can get energy consumption regularly, accurately, and fast – Power distribution is highly controlled – Local production and distribution are encouraged and greatly minimize distribution loss – Simplified and highly secured transaction procedures
Consumption	– Consumers do not influence the smart grid management, control, and operation	– Consumers can take part in the smart grid management, operation, and control as microgrid producers
Operations	– Customers often have limited choices of energy supplier – Operated manually and is vulnerable to unintentional or malicious attack – System updates and maintenance is done manually – Customers often have paper-based or digital contract – Centrally managed frequency and voltage control- difficult to manage with several distributed generators units involved – Prone to failures and can lead to a blackout	– Customers have several energy suppliers, many of which can be renewable sources – Automated and self-monitoring system minimizing bureaucracy – Automatically detect errors and self-troubleshoots – Customers can use smart contracts – Automatic frequency and voltage control can be done both locally and centrally – The system is not affected by some failed or unresponsive nodes
Service provider	– Unauthorized individuals/authorities can get access to sensitive data – Vulnerable to cyber threats – Sensitive information from the different stakeholders can leak without tracing the source	– The smart contract ensures that only eligible entities have access to relevant data – Highly secured and difficult to hack the system – Data encryption and Merkel hash in the distributed network ensure maximum security
Marketing	– Monitored by centralized governance – Price setting, billing, and other operations are governed centrally	– Decentralized, but can also be semi-centralized – Smart contract based decentralized and automated price setting, billing and other operations can be used

Smart grids and conventional grids differ primarily in the two-way flow of information between power grids and users (Heck et al., 2021). Blockchain has contributed to the growth of distributed accounting as an alternative technological innovation after the Internet that is tamper-proof, traceable, highly trusted, and decentralized. Blockchain can enhance data security in the power grid and contribute to the implementation of a trustworthy, effective, and reliable smart grid system. Several studies have already been conducted on blockchain in the energy sector.

First, the creation of power grids across the energy industry is at the heart of the process. Smart grids are also being developed in the context of blockchain. Some researchers have studied the growth of smart grids under Blockchain, but this research is not systematized and is still in the early stages. Most blockchain studies and smart grid combinations focus on deploying blockchain technology in a single part of the grid value chain, such as building secure smart grid data access and exchange systems based on Alliance Blockchain and secure distributed keyless blockchain signature methods. The evolving smart grid systems under the blockchain are not difficult to identify, but there is a scattering of existing research and a lack of integration.

Second, the organization, personnel, information, and resource system form the supply chain of the smart grid. Supply chains are inherently complicated, and inefficient supply chains can lead to major trust crises and need to be better shared and verified. In the application process, the blockchain works simultaneously with all the agents of smart networks, and different agents cooperate and influence each other. However, researchers have conducted limited research on the coordinated development of multi-agent systems from a stakeholder perspective. From the perspective of longevity, there are few studies on the integration of blockchain and smart grids, which need to be considered from three aspects: economic, social, and environmental.

Third, the scope for private chains is limited because the authenticity of the information can be easily doubted. Unlike private chains, public chains have much higher trust but cannot protect the privacy and security of participants. The above challenges have hindered the application and diffusion of public chains in the productive economy. Therefore, alliance chains exhibit "partisan decentralization" characteristics. While an alliance chain may cover only a limited number of subjects, security can be enhanced, costs reduced, and reliability increased.

Blockchain has been used for different applications in the energy sector. This chapter identifies several state-of-the-art benefits of using the technology to overcome the challenges discussed in the previous chapters.

4.1 BLOCKCHAIN APPLICATION FOR RENEWABLE ENERGY

4.1.1 Electric Vehicle (EV)

The widespread use of electric vehicles will be a valuable response to green travel and energy conservation challenges. However, electric vehicle users have problems with charging. The number of charging points for electric cars remains modest compared to gas stations, which is the main bottleneck limiting the widespread use of electricity. Many electric vehicles currently charge at stack operators and payment systems, but charging standards vary, leading to significant disadvantages for users. There is greater public acceptance of a unified, low-cost payment platform based on blockchain technology. On-time leasing of individual smart batteries for charging and common routing technology could also reduce the limited number of batteries for charging (Soto et al., 2020).

In the relationship between electric vehicles and the grid, there is no "vehicle to grid" incentives; battery quality cannot be guaranteed when using electric battery cascades. Energy Blockchain Labs, for example, has developed a blockchain for car reactions, battery blockchain data storage, and virtual currency stimulus certification (Peter et al. 2019).

The JuiceNet application in California, a market-driven IoT platform, was provided by eMotorWorks. With this blockchain technology, charging station owners can use JuiceNet to rent out charging station time to drivers (Patil et al., 2020). This means that the number of charging stations will increase. As a result, charging station owners can be compensated for their economic benefits at the same time. JuiceNet uses blockchain technology to store and process data in real-time, making it safer and more accessible for individuals to connect to and share charging services. Any motorist can download the JuiceNet application, monitor the chargers on the map, and select a charging station nearby.

Both renewable energy and electric vehicles urgently need similar solutions to expand their respective applications.

4.1.2 Decentralized (Peer to Peer) Energy Transaction

For a centralized, traditional energy trade, the energy Internet has become increasingly complex with the access of a large number of customers. Difficulties arise when a centralized organization is established, such as high operating costs and insufficient information protection. In addition, the commercial enterprise lacks confidence if there is no centralized management organization. These concerns can be addressed by introducing blockchain technology to energy generation. The P2P energy trading model based on the Blockchain system provides a low-cost, affordable, open, and trustworthy trading platform for energy networks. (Zhao et al., 2020) proposed a double-layer framework for Blockchain-based energy transactions in multi-microgrids to ensure decentralized trading, information transparency, and mutual trust between nodes in the trading market.

We view energy as a commodity and do not consider energy commodities as property. Energy exchange cannot be isolated from specialized monitoring processes, so such studies are insufficient to address the operational use of energy trading. (Kuznetsova et al., 2019) evaluated the security transactions in the grid and advised insufficient centralized power trading management. In addition, a management body with limited capacity needs to perform security checks and monitor the stopping of transactions. (Zia et al., 2020) studied the barriers to the adoption of energy trading over the Internet. They identified a three-tier structure based on blockchain technology (transaction, extension, and blockchain). The weak central authority is a specialized node within the blockchain system and monitors the parties involved in energy trading to ensure that the transactions run smoothly.

4.1.3 Certification and trading of carbon emissions

The rapid increase and concentration of greenhouse gases have led to a worldwide climate catastrophe. The United Nations has developed a carbon dioxide emission rights certification and trading mechanism under the Kyoto Protocol to encourage energy conservation and emission reduction, using the money for emission control (Chen et al., 2019). Based on the carbon emissions of different industries, China allocates a certain amount of carbon emission rights to emitting enterprises. The emission rights of firms with emission balancing rights can be purchased from firms that issue more than their allowances, or they can be sanctioned. Conversely, companies with additional emission rights can make a profit by selling them.

There are some challenges in the carbon market, such as the massive workload of emissions certification and difficulty tracking transaction data. Blockchain technology can provide a framework for smart carbon emissions trading and certification. This technology can track all tonnage of carbon and trading information, preventing information manipulation and asymmetry. For example, China Certified Emission Reductions (CCERs) are sold as "carbon tickets" for digital assets. Each carbon ticket has a unique ID, which is time-stamped and recorded as a blockchain. Automatically, smart contracts are used for carbon trading (Zhao et al., 2020).

This example shows the potential contribution to carbon emissions using blockchain. Each contributing node sends many error-prone files, while the normal development length exceeds one year. Meanwhile, it takes a long time to build traditional carbon assets, including companies, government regulators, trading of carbon assets, third-party verification and certification, etc. This framework will significantly reduce the cycle time for generating CO2 emissions and reduce the development cost of CO2 assets by 20% to 30% (Kong et al., 2019).

4.1.4 Physical Information Security

To make fair decisions, the system is guided by correct information. However, incorrect information can have disastrous effects on the system if it disrupts or attacks the information system. Power grid companies' most important security strategy is to create special communication links to isolate internal and external networks. Using data acquisition systems in a transmission network increases system costs during construction. At the same time, disruptions and attacks can occur when power system operators or public networks are used to communicate or exchange information. The origin of Stuxnet, an industrial computer malware, was discovered in 2010. This can penetrate a network of external computers via infected USB devices and attack the company's Internet. In 2015, the electricity information system in Ukraine was hacked, causing a massive power outage in the country (Kumari et al., 2020). Thus, electricity systems have improved their ability to withstand cyberattacks.

Decentralization, high redundancy, security, and privacy protection help to solve some of the security problems of the information and physical systems. However, there is currently limited research on the use of blockchain technology to solve security challenges in the energy Internet. (Yao et al., 2021) consider blockchains on the Internet from the perspective of private key loss, privacy violation, and protocol attacks on security problems. It also presents a strategy that constructs energy consisting of three components: architectural security, ontological security, and access control. The security measures control the entire lifecycle of the power blockchain communication system to efficiently meet the requirements for the future development of the energy blockchain.

4.1.5 Energy Transmission

In the face of increasingly critical environmental problems, the development method resulting from conventional fossil fuel energy is unsustainable. Therefore, there is a tendency to replace fossil fuels with clean and sustainable energy. While research in sustainable energy is progressing, relatively stable techniques such as wind or solar energy have problems with decentralized geographical coverage, poor management and consumption rates, and high energy costs, leading to major limitations in the use and commercialization of new energy sources (Hassan et al., 2019). In 2008, a future renewable energy transmission and management system was called the Internet of Energy model (Knirsch et al., 2020). The Internet of Energy consists of the new structure of power generation networks, networked storage systems, and the Internet.

Conversely, the quality of this platform is challenged by corporate and user service. The energy Internet encompasses a broader range of power and participants than existing power grids. It changes the information exchange approach to create a new energy supply with highly integrated and complementary information across multiple energy sources (Li et al., 2019d). Blockchain-based energy systems will offer promising solutions for managing energy transmission among heterogeneous renewable energy systems.

4.1.6 Power-to-X

Power-to-X uses electricity to produce other products to store energy. Power-to-X can be power-to-ammonia, power-to-chemicals, power-to-fuel, power-to-gas, power-to-hydrogen, power-to-liquid, power-to-methane, power to food, power-to-power, and power-to-syngas. Power-to-X offers the unique possibility of storing excess renewable energy generated when demand is relatively low, which can increase the economic value of renewable energy generation by facilitating classical storage arbitrage (Byfield & Vetter, 2016). With power-to-X, enormous amounts of energy may be kept for lengthy periods, making it suitable for seasonal storage. Because many places have significant seasonal solar, wind, and hydroelectric output variability, this could be especially advantageous for systems with high renewable penetration. In addition, as renewable energy deployment continues to expand, power-to-X also has the potential to help decarbonize other sectors of the economy, such as industry and transportation, that have long plagued carbon reduction experts.

The application of blockchain smart contract technology for tracking and tracing the type of energy, conversion history, and data support for transparency, credibility, and automated enforcement for future carbon trading.

4.1.7 Internet of Energy

It is also argued that the Internet of Energy (IoT) is the basic research guideline to address the current problems in the energy sector. (Faizan et al., 2019) says that society will enter an IoE system that combines new energy and communication technologies with conventional fuel depletion and ongoing global environmental degradation. Japanese academic institutions have focused on creating the digital grid system and proposed the energy Internet "Power Router" by the Japan Digital Grid Alliance. (Hu et al., 2020) provides a preliminary description of the energy Internet: the energy Internet is a closed loop in which renewable energy is widely used as the main energy source, and other gas grids and transportation systems are closely connected. It is built on the Internet and other advanced IT systems, and the power grid is at the center. More specifically, the energy Internet described in (Li et al., 2019c) includes an Internet-connected smart power grid platform, Big Data, cloud computing, and other leading ICT platforms. Advanced electromechanical devices and smart management technologies in the future power system will be used to integrate horizontal, cross-source, complimentary, comprehensive, hierarchical synchronization and data, source-grid-neutron-to-storage.

As shown below, the IoE offers precise metering, wide-scale multi-source cooperation, intelligent control, and open trading (Wu et al., 2021, Yao et al., 2021, Chen et al., 2019, Faizan et al., 2019).

1) Wide-area multi-source cooperation: IoE provides wide coverage, high reliability, and many participants. Coordinate the planning operations of large-scale power generation bases, power transfer, and end-use power utilization, including multi-source cooperation. Through cooperation, participants can reach an agreement and maximize profits.

2) Accurate measurement: This is the prerequisite for regulating the circumstances of the operation of various energy and computation systems. Therefore, the IoE must also address participants' consensual reliance on metering data and accurate measurement.

3) Open trade: The technology takes advantage of modern society with huge centralized grids and local distribution networks. Without discrimination, any energy source can access the Internet. Energy producers can also be electricity consumers, and consumer involvement is greatly enhanced. The IoE provides various energy services anytime and anywhere to promote demand, support services, and buy and sell electricity. By reducing the peaks and troughs of the energy IoE, its operational performance will be improved.

4) Intelligent control: Smart approaches such as large-scale data processing and web learning are essential and enable a wide range of dispersed energy sources. From generation to use, the entire process depends on intelligent control technology for flexible and efficient energy conversion and optimization of transmission performance.

Blockchain can support the construction of a distributed IoE with autonomy, scalability, and intelligent control to realize future renewable energy planning, management, and application.

4.2 BLOCKCHAIN FOR THE SMART GRID OPERATION AND MANAGEMENT

Blockchain offers a new solution to these challenges. It minimizes data management, fair incentive mechanisms, regulatory costs and technical issues, transaction fees between distributed nodes, speed of resources, and price adjustment issues. It can also increase transparency among stakeholders, ensure data security and privacy, simplify the energy demand and supply chain, and minimize distribution losses.

Blockchain application in the energy sector is an ongoing area of research and development (Hasse, et al., 2016), however, most of these applications have not yet progressed beyond the pilot stage. One notable example is the Brooklyn Microgrid (Brooklyn (BMG), 2019) which allows local solar energy consumers to exchange data via blockchain. Another example is the UK's Electron project (Electron, 2020), which uses a blockchain-based platform to enable grid operators, systems, local energy markets, and distributed energy sources to participate in multiple grid optimization markets with different energy assets. Countries worldwide recognize the potential applications of blockchain in the energy sector. For a list of efforts by companies to implement Blockchain in the energy sector, see (Foti & Vavalis, 2021). Figure 4 shows a potential Blockchain infrastructure for managing, controlling, and operating smart grids (Aklilu & Ding, 2021).

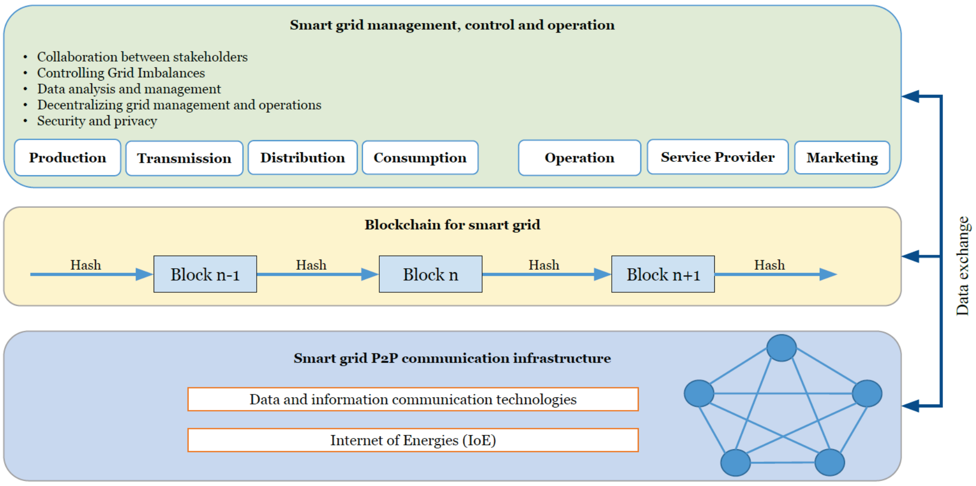


Figure 4. Blockchain infrastructure for smart grid management, control, and operation.

Several studies have also been published that address various blockchain applications, challenges, opportunities, and future trends. In (Foti & Vavalis, 2021), the authors provided an up-to-date and comprehensive summary of Blockchain use for smart grids by analyzing a number of peer-reviewed articles, research results, and entrepreneurial projects. The authors (Musleh et al., 2019) presented an overview of blockchain-based solutions to smart grid challenges and their advantages and disadvantages. The article identified relevant blockchain-based applications, especially at the cyber-physical level of the smart grid. In (Andoni, et al, 2019), the authors conducted a survey to systematically identify potential blockchain implementations for smart grids, associated challenges, and opportunities. A comprehensive overview of blockchain applications for future decentralized smart grids is provided in (Mollah, et al., 2020). The article discusses that current smart grids face several challenges such as scalability, transparency and extensibility, high computational cost, availability of attacks, and inability to control future power supply consisting of multiple components.

Table 5 summarizes recently published studies in this area. The table also describes the approach of the study compared to our article. Some articles address the use of blockchain in smart grid marketing, grid decentralization, data aggregation and storage, and security and privacy mechanisms. Relevant challenges for grid management and operation arising from stakeholder collaboration, grid imbalances, data analytics, and management have not been addressed in existing review articles. Moreover, the challenges covered are often viewed from the retail perspective. This work includes the challenges not considered in other studies and recent developments in smart grid management, control, and operation.

Table 5. Summary of typical surveys and reviews on blockchain challenges for smart grid management, control, and operation.

Ref	I	II	III	IV	V	Descriptions
(Andoni, et al, 2019)	L	L	M	M	L	Conducts a systematic review of the potential applications of blockchain for energy company operations, wholesale energy trading and supply, energy imbalance settlement, digitization of IoT platforms, and P2P trading and distributed energy supply.
(Mollah, et al., 2020)	L	L	M	M	L	Provides a comprehensive overview of blockchain applications for AMI, the distributed energy trading market, monitoring, control, and metering, electric vehicle and charging station metering, and microgrid operations.
(Wang & Su, 2020)	L	L	L	L	L	Reviews research progresses of blockchain technology for the energy sector, particularly on distributed energy systems, optimization of energy trading, electric vehicles, smart device connection, intelligent control, and supporting environmental challenges.
(Alladi, et al., 2019)	L	L	M	M	H	Provides an overview of blockchain applications for P2P energy trading infrastructure, electric vehicle energy trading, asset maintenance security, energy generation and distribution, and privacy and security techniques.
Musleh et al., (2019)	L	L	L	M	M	Reviews various aspects, advantages, and disadvantages of using blockchain for energy trading, microgrid operations, EV, and cyber-physical security.
Samy, et al., (2021)	L	L	L	H	L	Provides an overview of blockchain applications for energy trading, infrastructure management, and smart grid operations.
Hasankhani, et al., 2021)	L	L	L	H	M	Provides current improvements in blockchain applications for smart grids, and identifies opportunities, challenges, and potential solutions in various areas of the smart grid.
Yapa, et al., (2021)	M	L	M	M	M	Analyzes the applicability of blockchain for Smart Grid 2.0 to facilitate grid decentralization.
Xie, et al., (2019)	L	L	L	L	M	Provides an overview of blockchain applications for various areas of smart cities, including smart grids for energy trading, improving data security, renewable energy financing, and Thing-to-Thing energy trading.
Aggarwal, et al., (2021)	L	L	L	L	L	Reviewed recent developments in energy trading, taxonomies, challenges, and potential solutions.
Ante, et al., (2021)	L	L	M	M	M	Provides a bibliometric analysis and review of blockchain implementations for energy marketing, data exchange and security, energy management and scalable systems, information transfer, P2P energy sharing, and trading in microgrids among others.
Zhu, et al., (2020)	L	L	L	L	L	Presents blockchain applications for China's energy sector. The article focuses in particular on energy financing, trading, consumption, and Energy Internet.
Lui, et al., (2021)	L	L	L	L	H	Provides a comprehensive overview of blockchain technology solutions for smart grid transformation from the perspective of technological advances in its industrial applications, challenges, and opportunities.
Zhuang, et al., (2020)	L	L	L	L	M	Presents the latest blockchain ideas, architectures, and technologies for cybersecurity in the smart grid.
Bao, et al., (2020)	L	L	L	M	M	Comprehensively present existing blockchain applications for P2P trading of Electric Vehicles, carbon emission trading, etc.
This report	H	H	H	H	H	Provides a systematic overview of blockchain in the smart grid for stakeholder collaboration, data analytics and management, grid imbalance control, decentralization of grid management and operations, and security and privacy.

I: Collaboration among stakeholders, II: data analysis and management, III: control of grid imbalances, IV: decentralization of grid management and operations, and V: security and privacy; H: High coverage, M: Medium Coverage, L: Low coverage

Smart grid management and control is an important issue due to the diversity and number of DG units. Demand-driven control and optimization of network management are the focus of research. Feasibility and use case studies have been conducted on using blockchain for smart grid management, control, and operation (Foti & Vavalis, 2021). A systematic review of blockchain applications for the energy sector at the national and institutional levels is presented (Wang & Su, 2020). In addition, (Suciu, et al., 2019a) and a related paper by (Suciu, et al., 2019b) explored how blockchain can be used in smart power management in the SealGrid platform which allows users to monitor power consumption in real-time without compromising security. The authors (Mollah, et al., 2020) emphasize that the future of the smart grid must provide some level of security by 1) ensuring that unauthorized people cannot access information; 2) preventing unauthorized people from modifying the data; 3) cryptographic solutions provide adequate data protection; 4) denying authorized permission and granting access to those with the proper privileges; 5) authentication that ensures entities performing a specific task cannot deny their action; 6) developing a fault-tolerant network that is resistant to various attacks; 7) more efficient monitoring; 8) Using advanced privacy technologies to protect information disclosure; and 9) Promoting thrust, transparency, and democracy among all stakeholders. This subsection summarizes blockchain-based applications for smart grid management, control, and operation based on the challenges discussed in Chapter 2.

4.2.1 Collaboration between Stakeholders

The consortium blockchain supports the virtual power plant (VPP) control system, improves operational activities, optimal scheduling, and efficient trading, and solves the lack of real-time performance, high transaction costs, and information security (Li, et al., 2019b). Exploiting the similarities between VPP and blockchain in terms of data injection and information communication between different nodes within the system, the authors developed a VPP control system model based on blockchain. The model integrates discrete power supply, load, and other smart devices to share data with two Blockchain systems, one technical and one commercial. The technical blockchain controls the process by connecting to the SCADA system via Ethernet to support power transmission, balancing, voltage, and frequency control, and to provide stable transmission and scheduling for the VPP. The commercial blockchain supports the process of energy quantity, price, transaction contracts, etc. Galici, et al., (2021) proposed a Blockchain-based data ledger to store and track public buildings' energy generation and consumption. The proposed platform facilitates transparency among stakeholders by making raw data available to the public to provide citizens with sustainable, affordable, reliable, and modern energy services. This raw data's availability facilitates data analysis for research and development, production and distribution controls, and resource management.

4.2.2 Controlling Grid Imbalance

Blockchain provides a mechanism to synchronize data from a variety of sources. These can help grid operators monitor different energy resources simultaneously, control voltage and frequency, and coordinate communication between different energy stakeholders. Blockchain can also help regulate voltage and frequency on the smart grid. Voltage and frequency fluctuations can lead to power outages. This can be solved by continuous monitoring of power generation and consumption. But the increasing number and variation of energy sources make the control system unstable. With blockchain technology, we can accurately and continuously determine the amount of energy produced and consumed, so that the grid is resilient to unexpected frequency or voltage overloads. Blockchain-based production control for distributed generation systems to avoid grid congestion is proposed by (Danzi, et al., 2017). In addition, (Madhu, et al., 2019) have proposed a framework for using blockchain to monitor PV-based electric vehicle charging stations to regulate load frequency. The author's proposal integrates blockchain with a smart energy controller to optimally manage grid capacity considering load frequency and PV availability. The proposed framework improves user privacy, immutability and transparency of energy data, energy tracking and availability, and user sharing.

4.2.3 Data Analysis and Management

Blockchain as a distributed database system creates decentralized tamper-proof, but traceable networked copies of the data under a certain consensus verification. Blockchain can support smart grid data analysis and management, data protection, and aggregation (Dong, et al., 2018). Along with the diversity of distributed generation (DG), the smart grid is also changing its data aggregation and analysis mechanisms. Aggregators such as Demand Response (DR) and Virtual Power Plant (VPP) provide grid services to a wide range of energy resources. However, these aggregation mechanisms pose challenges to operators due to their large-scale and complex deployment, requiring management and control. Establishing trust and transparency between DG entities and aggregators is also important to maintain short- and long-term interaction. To address these challenges, some blockchain-based solutions have already been proposed. In (Liang, et al., 2020), a blockchain-based power grid data management architecture is proposed to realize binding data recording and business collaboration among multiple nodes. The proposed framework promotes collaboration among data aggregation and analysis processes, provides real-time awareness of data sharing to various stakeholders, simplifies the process of data access, coordinates data application, and facilitates technical support for smart grid data management and operation. The authors (Mnatsakanyan, et al., 2020) propose a blockchain-based decentralized aggregation mechanism that handles all transactions between decentralized energy owners, demand response, and virtual power plants. Blockchain can also be used for decentralized data collection, analysis, and management to minimize data communication and storage costs (Aderibole, et al., 2020). In (Fan & Zhang, 2019), a consortial blockchain-based multidimensional data aggregation and control mechanism is proposed to ensure the security of stream data during communication. The proposed architecture creates a dynamic stream data control and operation architecture by simplifying the low data aggregation efficiency, computational complexity, feedback accuracy, and key management and data repair. Integrating blockchain with advanced metering systems could help utility operators predict future consumption needs by monitoring the continuous and accurate immutable data provided by blockchain technology.

4.2.4 Decentralizing Grid Management and Operation

A distributed data aggregation and storage mechanism using blockchain to secure grid sensor data was proposed by (Liang, et al., 2018). The authors (Aderibole, et al., 2020) identified three Blockchain-related characteristics (decentralization, thrust, and incentives) to analyze the smart grid-related literature and identify requirements for NIST conceptual models. According to the authors, blockchain enables decentralized collection and verification of metering applications at multiple levels. It solves the problem of centralized data collection that could affect smart grid performance. The authors also describe that using blockchain for smart grids facilitates decentralized energy trading mechanisms, improves the operational efficiency of VPPs, enables demand-side management systems in microgrids and consumer cities, renewable energy tracking, and edge computing for decentralized P2P interactions, among others. In (Luo, et al., 2021), decentralized data aggregation for microgrids using Pallier and PBFT homomorphic encryption is proposed to protect user privacy and data integrity in public storage and sharing. The authors have also proposed an automatic and distributed solution for energy distribution in a microgrid using Ethereum Smart Contract. In (Nurgaliev, et al., 2019), the authors propose a decentralized energy regulation and exchange application based on Ethereum smart contracts. Their framework minimizes reliance on a central authority, improves the efficiency of renewable energy resources, and addresses privacy and security issues. Smart contracts are used by (Cioara, et al., 2020) to propose a blockchain-based platform for peer-to-peer energy trading, decentralized energy management, energy flexibility aggregation, and community-based VPP operation. In (Zhang, et al., 2019), a blockchain-based keyless decentralized authentication architecture between service providers and end-users in the smart grid is proposed to improve certification reliability and non-repudiation. In this approach, smart meters send a request and then receive the response through a consortium-based blockchain network that does not require a trusted agent. Ethereum smart contract with blockchain is used (DeCusatis & Lotay, 2018) for interaction between energy generation and consumption between different smart meters in different buildings. The framework automatically monitors the availability of energy reserves and smart meters and initiates transaction requests. The authors also proposed a digital identity management algorithm that authenticates smart meters and blockchain ledgers to mitigate port scans and port-based attacks on the Ethereum blockchain. In (Li, et al., 2019a), the authors investigated the feasibility of using blockchain for transactive distributed grid management and operation of interconnected microgrids to optimize the financial and physical operation of power grid systems.

It has been shown that these Blockchain-based systems can support the physical layer of the smart grid. Aggregation, analysis, and management of grid data can improve the missions of transmission system operators (DSOs) by providing accurate data on electricity generation, distribution, and consumption. Blockchain, along with various underlying technologies, can facilitate decision-making at different levels of grid operations. However, maintaining data security, integrity, and privacy in the grid environment for data aggregation and analysis is a complex issue that requires thorough investigation.

4.2.5 Security and Privacy

Traditional smart grids have been subjected to several malicious cyberattacks over the years, using various methods such as Denial of Service (DoS) to gain unauthorized control over the grid, resulting in partial or complete power outages. Studies have shown that blockchain, whose main characteristic is the immutability of data, can provide a solution to this problem. There are several known attacks on smart power grids. One of them is the jabbing attack, in which the attacker installs a malicious smart electricity meter that sends false data, causing desynchronization and power interruption. The puppet attack sends a signal to the node. The attacker then controls the node and sends more signals into the network, causing the smart meter network to become unstable.

Another example is the stack smashing attack, which compromises the application layer of the network and leads to the disclosure of sensitive data. An experimental attack, on the other hand, makes the smart grid layer vulnerable to DoS attacks (Kumar, et al., 2019). A comprehensive review of blockchain in smart grid for cybersecurity from application and technology perspectives was conducted by (Zhuang, et al., 2020).

Several promising blockchain-based techniques have been proposed to address the smart grid's privacy and user security challenges. Privacy-Preserving Energy Transactions (PETra) is described in (Laszka, et al., 2017) as a secure distributed ledger-based energy trading solution that provides anonymity for communication, bidding, and trading. The framework enables secure and verifiable trading of energy futures, preserves prosumers' privacy, and allows distribution system operators to regulate trading and enforce security rules. The proposed framework was later extended by (Bergquist, et al., 2017) to illustrate communication and transaction anonymity. The authors (Guan, et al., 2018) presented a scheme for efficient data aggregation and privacy protection based on blockchain. In addition, (Kamal & Tariq, 2019) proposed Blockchain-based lightweight security solutions for advanced metering infrastructures to prevent man-in-the-middle attacks and data tampering through timely adversarial node detection, localization, and provenance through Blockchain. A permission-based blockchain edge model for smart grid networks to ensure data privacy and energy security is proposed by (Gai, et al., 2019). The proposed model aims to ensure traceability of energy consumption while protecting end-user privacy, enabling optimal energy management, and enabling controllers to assess the identity of the edge device in smart grid networks.

A novel cybersecurity architecture for smart grids based on blockchain to improve data security is proposed by (Olivares-Rojas, et al., 2019). The algorithm leverages advanced metric infrastructures such as smart meters and virtual power plants and uses an edge-fog cloud computing architecture. In (Casado-Vara, et al., 2018), the authors show how the immutability of the blockchain can be used to detect non-technical frauds such as energy theft, metering errors, billing process errors, etc. This helps utilities control and monitor the power distribution network. In (Liang, et al., 2018), a blockchain-based smart grid protection framework against cyberattacks is presented to improve the power grid's self-defense capabilities, robustness, and security. In addition, (Gao, et al., 2018) proposed a blockchain-based solution backed by a smart contract to create a temperature-proof system to protect consumer data collected and transmitted in the smart grid system. The proposed system provides transparency, auditability, and immutability

Blockchain has also been used for access control systems in the smart grid. In (Zhou, et al., 2019), the application of Blockchain for identity-based combined encryption, signature encryption, and signature encryption scheme for the smart grid is proposed, which solves the pressing problem of a private key generator, ensures secure key management, and involves more users in the daily management of the smart grid.

Table 6 summarizes the various blockchain applications that have been proposed in recent years for the management, control, and operation of smart grids. Blockchain technology could solve these challenges by providing a decentralized platform where all participants can share information equally. The technology could enable all participants to collaboratively create a platform without having to trust each other (Mattila, 2016). The adoption of blockchain in the energy sector has several benefits: Energy blockchain technology promotes decentralized production and distribution of low-voltage energy systems (Li, et al., 2019b). It also supports simplified multi-level systems (Wang & Su, 2020), in which energy producers, distribution system operators, transmission system operators, and consumers can communicate directly with each other to ensure the operation process. In addition, blockchain, in combination with smart contracts, enables efficient smart grid management (Mylrea, 2019). Using predefined consensus rules, smart contracts send signals to all nodes to ensure legitimate transactions. In this way, all energy storage flows can be controlled automatically, which contributes to the accuracy of the balance between supply and demand (Brilliantova & Thurner, 2019). Blockchain can also record, store, and distribute all energy transaction data, ensuring decentralized security of all energy flows and business activities (Wang & Su, 2020).

Table 6. Blockchain-based solutions to address challenges in smart grid management, control, and operations

Blockchain Application areas	– Blockchain-based solutions to address the challenges	Ref.
Collaboration between Stakeholders	– Facilitates trust and transparency between stakeholders and the public – Automatic monitoring and maintenance of the smart grid – Enables resource allocation, tracking of environmental indicators – Improves efficiency of renewable energy sources – Improves the digitalization of the grid and enables new applications for the power system – Facilitate the role/influence of microgrid prosumers in the management and operation of the smart grid	(Li, et al., (2019b); Galici, et al., (2021))
Controlling Grid Imbalance	– Regulation of voltage and fair distribution of production between distributed generation units – Enables a temperature-safe system to protect customer data collected and transmitted to the smart grid	(Danzi, et al., (2017); Madhu, et al., (2019)
Data analysis and management	– Protection of authenticity and correctness of aggregated data – Creation of immutable data structures that cannot be modified. – Highly scalable and supports for micro transactions – Enhancement of the architecture for the power management system to monitor power consumption in real-time – A secure data aggregation based on encryption – Enabling a multi-dimensional data aggregation control mechanism for the smart grid – Decentralized aggregation mechanism to handle all transactions between different smart meters	(Mnatsakanyan, et al., (2020); Aderibole, et al., (2020); Fan & Zhang (2019); Liang, et al., (2020))
Decentralizing grid management and operations	– Improve authentication and non-repudiation – Support the power management process without a trusted party. – Participation in distributed computing to reduce the VPP's computational load – Promotion of decentralization – Improve transparency, digitize the grid, and enable new applications for the power system – Support advanced metering infrastructure control systems to improve operational activities, optimal planning, and efficient trading – Enables traceable energy management on the smart grid	(Aderibole, et al., (2020); Dong, et al., (2018); Liang, et al., (2018); Luo, et al., (2021); Nurgaliev, et al., (2019); Cioara, et al., (2020); Zhang, et al., (2019); DeCusatis & Lotay, (2018); Li, et al., (2019b))
Security and privacy	– Create immutable data structures that cannot be modified – Improving cybersecurity and privacy for smart grids – Improving security and privacy, information security, access control – Localization and provenance – Solves the problem of lack of real-time performance, high transaction costs, and information security – Timely identification of adversarial nodes	(Liang, et al., (2018); Kumar, et al., (2019); Zhuang, et al., (2020); Laszka, et al., (2017); Bergquist, et al., (2017); Guan, et al., (2018); Kamal & Tariq (2019); Gai, et al., (2019); Olivares-Rojas, et al., (2019); Casado-Vara, et al., (2018); Gao, et al., (2018), Zhou, et al., (2019))

5 Discussion

A blockchain-based smart grid requires systematic work from design to implementation. It needs support from both technical and non-technical aspects. Localized standalone solutions cannot make the Blockchain system fully functional. A lot of fundamental work is needed to ensure efficient management, control, and operation of Blockchain-based smart grids. Further discussion and research directions are addressed below.

5.1 COLLABORATION BETWEEN STAKEHOLDERS

The introduction of blockchain technology into the smart grid, a widely accepted and well-functioning system, is always a challenge to harmonize the collaboration between all stakeholders.

1) **A Better understanding of the needs and the future**. All smart grid stakeholders (energy producers, transmitters, distributors, consumers, regulators, coordinators, etc.) need to understand and evaluate current challenges and future trends in energy management and their environmental, social, economic, and regulatory implications to accept and implement them. Some of the resulting issues need to be addressed.

2) **Effective coordination and consensus mechanism**. Energy stakeholders will be participants, contributors, and beneficiaries of the blockchain system whose interests and responsibilities do not fully align but must collaborate and participate in a blockchain-based smart grid system. This requires all stakeholders to be able to achieve an effective coordination and consensus mechanism with the technical support of the Blockchain, and also to thoroughly engage with this decentralized, entirely new system, technical means, and business model.

3) **Advanced technical tools and newer administrative systems**. Increased collaboration among regulatory, administrative, technical, and commercial stakeholders is needed to develop coherent blockchain systems that can improve existing systems. This collaboration must be based on more modern technical tools and newer administrative systems. Relevant technology development outcomes need to be tested, validated, and improved in real-world smart grid systems.

4) **Seamless integration**. Blockchain-based system technology must address and improve upon the shortcomings of current systems and provide scalability, speed, accuracy, and security, as well as seamless integration with existing advanced metering infrastructure.

5.2 CONTROLLING GRID IMBALANCE

With the development of smart grids, the need for applications and integration of various renewable energy sources, including managing multiple imbalances in the blockchain system, is increasing.

1) **Synchronization**. Blockchain-based smart grids require mechanisms to synchronize data from multiple sources to balance the associated imbalances resulting from 1) voltage and frequency shifts in the grid system itself, 2) continuous dynamic changes in energy generation, transmission, distribution, and demand, 3) changing energy consumption patterns and quantities, and 4) flexible and variable energy exchange and trading.

2) **Integration and interaction**. Deep integration and interactive control technology between blockchain and different parts of the grid is an urgent problem to solve. The sharing characteristics, timely data updates, and stability of the architecture possessed by blockchain technology provide a good technical basis for solving these imbalance problems.

3) **Automation control**. Further research is needed to investigate the scope of blockchain design and implementation, the associated interfaces to each control system, and blockchain-based automation control and coordination technologies.

4) **Information exchange**. The main mission of Blockchain-based decentralized grid management and operations is to ensure secure information exchange among relevant stakeholders, improve the supply and demand chain, facilitate the participation of professional renewable energy consumers in energy markets, control congestion with automated frequency and voltage monitoring systems, and protect critical grid resources with real-world implementations are all areas for future research.

5.3 DATA ANALYSIS AND MANAGEMENT

Blockchain-based smart networks greatly extend the digitization of existing power grids. So data analysis and management is a big issue in the context.

1) **Big Data**. Each electronic and digital component of the grid continuously generates various types of data to control and maintain the grid system and support its commercial operations. The complex and large-scale decentralized system implies that the complex and volatile distributed data needs to be accumulated, fused, analyzed and rationalized for use.

2) **Data fusion**. Advanced data processing and management technologies need to be combined with blockchain systems to address the challenges of the 3Vs (volume, velocity, and variety) of data in the smart grid, high scalability and scalability, diversity and heterogeneity of data types, and timeliness of data processing.

3) **Off-chain data processing**. Blockchain itself does not have the rationalization design and processing ability to handle big data. Still, the combination of smart contract and off-chain data processing can allow the refined core data to enter the main chain of the Blockchain. Most of the lengthy and trivial local data analysis and processing are processed outside the localized chain and controlled by the smart contract for

relevant data analysis, which will significantly improve the capacity and efficiency of smart grid based on blockchain. This will greatly improve the capability and efficiency of data analysis and processing blockchain-based smart grids.

4) **Data techniques**. Advanced data techniques such as machine learning, deep learning, etc. need to be introduced to help analyze all kinds of big data related to smart grids.

5.4 DECENTRALIZING GRID MANAGEMENT AND OPERATIONS

Blockchain-based decentralized management and operation of the smart grid are very different from the traditional centralized management and operation model.

1) **Extensive decentralization.** Traditional centralized management has centralized managers and controllers coordinating the global management of all types of grid issues and operations. The Blockchain-based smart grid brings the concept of decentralization to the grid system in terms of technology, data, business, and its management and operations. It also implies a complete change in business logic and technical systems, as well as a change in the management model.
2) **Evolution from decentralization**. Decentralization not only avoids the risk of a single point of failure in a complex smart grid, but also brings an evolution of the system, including 1) autonomy of individual nodes, 2) automation of the system's business execution (code execution based on smart contracts), and 3) resilience of the system with high fault tolerance and system robustness.
3) **Deep centralization**. Decentralized management and operation can facilitate and accelerate network operation decisions at various levels, making frequent and tedious day-to-day business and operations extremely efficient.
4) **Updating of management model**. The redesign and implementation of fully decentralized grid management and operation require further research on the technical implementation of the system at all levels and the adaptation of the management rules and concepts of the existing system.
5) **Mitigating the risks associated with decentralization**. Attention must also be paid to how to avoid the risk of system chaos and disorder that may arise after decentralization.

5.5 SECURITY AND PRIVACY

Blockchain is a distributed ledger database system, and also poses some threats to data security.

1) **Cyberattacks on the blockchain**. Large-scale cyberattacks cannot disrupt the online services of the blockchain and even cause data loss.

   a) **Enlarged attack surface**. As with any IT system, the same cyberattacks are on the rise and remain a threat to the smart grid. The performance of a blockchain-based smart grid relies heavily on the autonomous management and automated operation of the technical system due to its decentralized and efficient architecture and operation. However, due to the ever-growing attack surface of the smart grid system, the blockchain-based system needs to maintain the security of the grid business, the security of the grid system, the security of the grid data, and the privacy of all participants. In addition, the blockchain itself may also be exposed to new cyberattacks or data-oriented intelligent attacks. These issues need to be properly monitored and researched.

   b) **Off-chain attacks**. Since the blockchain system is supported by and serves other parts of the smart grid, any potential attacks outside the chain may eventually affect the performance of the blockchain system, e.g., injecting manipulated data into the blockchain, reading data from the blockchain through malicious manipulation, etc.

   c) **Local vulnerability vs. global security**. The security vulnerability of each component and the protection of the operation process of each functional area must be considered in the development of the future blockchain system.

   d) **Hierarchical protection**. The hierarchical structure of the blockchain (including the functional hierarchy, data hierarchy, business hierarchy, etc.) and the cooperation between multi-branch chains also help to avoid security risks and increase the security and resilience of the system and data.

2) **Verification of legal blocks**. New blocks are constantly being added to the blockchain. The big issue is ensuring the legal blocks are reasonably selected and verified. Consensus protocols mainly perform this task. Potential vulnerability or incomplete design of the consensus algorithms can jeopardize this.

3) **Forks of blockchain**. Blockchain protocol or version update can lead to a hard fork. The creation of new blocks in the blockchain can lead to a natural soft fork. Whether a hard fork or a soft fork, the structure of the blockchain may change, thereby affecting the performance of the blockchain system.

4) **Protection of smart contracts**. Smart contracts contain important application logic and services. Any improper modification of smart contracts can lead to the disruption of blockchain services. Therefore, it is important to ensure the security and integrity of smart contracts. Of course, hash technology can adequately ensure the security of smart contract data. But for contracts with large granularity outside the chain, maintaining the security of the contract is still a challenge.

5) **Data privacy and ID management in blockchain are challenging**. The data entering the blockchain is transparent to all users. If the ID management is not in place, a large amount of private data can leak out. Generally, the user ID, data ID, and privacy-related data have been translated and stored off-chain before entering the blockchain. If this process fails, privacy cannot be protected. While blockchain technology cannot guarantee privacy directly, advanced cryptographic measures can be incorporated to protect data. The following are some approaches to safeguard the privacy of the devices concerned: Zero-Knowledge Proof (ZKP), the Elliptic Curve Digital Signature Algorithm (ECDSA), and the linkable signature ring.

5.6 LEGAL AND REGULATORY

The regulatory agencies promote active user involvement in the energy market and the development of community energy infrastructure. When it comes to drastic modifications in the main grid framework, the grid system doesn't facilitate energy exchange between producers and consumers, nor does it support the adoption in that framework of the distributed leader (Mollah et al., 2021). In particular, for the P2P trading system, new types of contracts must be devised, and energy pricing modifications must be made to promote such services. In the existing grid system, such issues are highly regulated. For these circumstances, although blockchain technology has shown value in informing a microgrid, it is very difficult to incorporate the technology into the power system framework without modifying the power systems. The ideal future for a solid renewable energy business is based on a good understanding of technology, operations, strategy, policy, and regulation.

6 Implementation

6.1 BLOCKCHAIN SYSTEM ARCHITECTURE

The renewable energy blockchain system is an integrated technical system that includes renewable energy systems, communication network systems, blockchain systems, and blockchain-based application systems. The systems are interconnected and communicate through various data streams. See Figure 5.

In a blockchain-based renewable energy system, electricity generation and consumption data are transmitted through smart meters. Each stakeholder is a node in the blockchain. All relevant transactions are transmitted to the grid. The transmitted data, including electricity statistics and transaction data, is then confirmed in the blockchain ledger according to the consensus protocol. The consensus protocol can be switched between PoW and other consensus algorithms in the simulation. The blockchain ledger manages transactions, balances, and historical information.

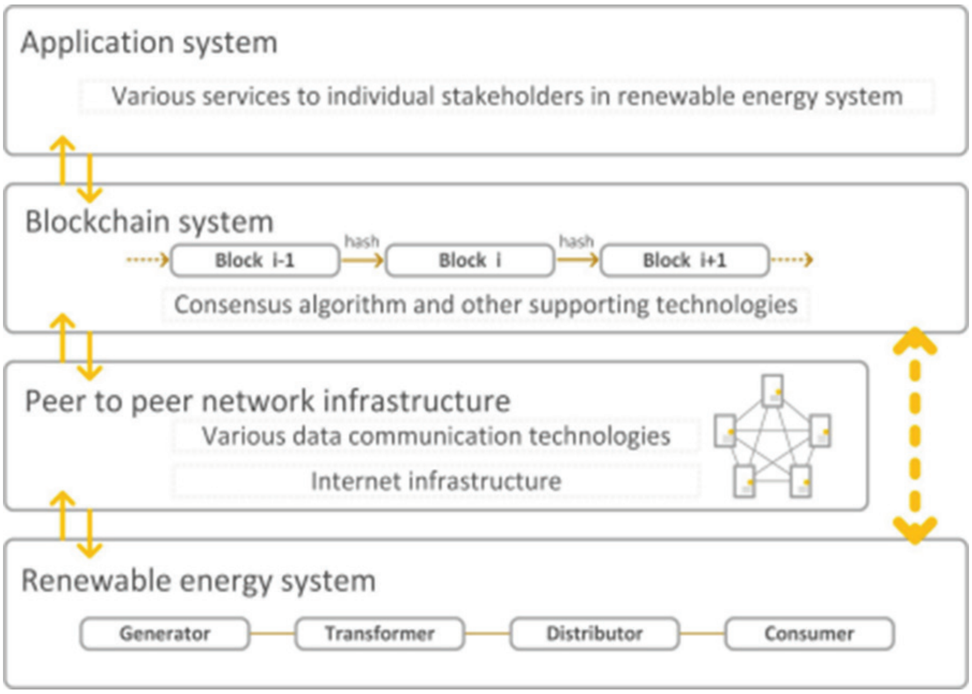


Figure 5. Blockchain System Architecture

The community committee can set up the blockchain system as an alliance blockchain. All participants register in the system and receive authorization and authentication information.

6.2 DATA FEED TO THE BLOCKCHAIN FROM THE POWER GRID

The Blockchain system is a system for storing and managing data. Once the data enters the Blockchain system, it is recorded in history. The history of the Blockchain cannot be changed. Therefore, the data feed is directly related to the data quality of the Blockchain and the quality of the system services. Data injection involves several important aspects:

1) What data needs to be injected into the blockchain system? This involves the actual business requirements of the application, i.e., what data will be used in the future.
2) How will the data be entered? Manual input and automated input are the common methods. To ensure data accuracy and avoid human error, automated input is the ideal way. This places requirements on existing renewable energy systems; these systems can provide automated interfaces for data output that feeds directly into the blockchain system. Automated data input from smart meters and VPP (virtual power plan) to blockchain will speed up data processing and its accuracy (Cioara et al., 2021) (Yang et al., 2021).
3) How can the correctness of the data be ensured? This requires appropriate operations such as screening, inspection, cleaning, and validation of the data entered. In the early days of data entry into the blockchain, blocks may be revoked for technical reasons, so it is also important to ensure security before and after data entry. Relevant data protection technologies will help protect the security of the data.

6.3 BLOCKCHAIN DEPLOYMENT FRAMEWORKS

The famous blockchain deployment frameworks used in recent studies of blockchain-enabled systems, namely Ethereum, Hyperledger Fabric, FISCO BCOS, Corda, and EOS are discussed in this section. Different blockchain frameworks have distinguished properties. For instance, the Public blockchain offers consistent performance, the private blockchain offers robust security, and consortium blockchain offers more customization options. From the thorough investigation of the literature, in table 7, blockchain frameworks are elaborated with key characteristics, including blockchain category, smart contract enabled with applied language, consensus algorithms, etc.

6.3.1 Ethereum

Ethereum is a decentralized, open-source blockchain framework that allows users to create smart contracts. Ethereum is a permissionless blockchain platform, launched in 2015, deployed the Proof-of-Work (PoW) consensus algorithm, and has a native cryptocurrency known as Ethereum (Buterin, 2013). Furthermore, Ethereum allows smart contract implementation written in Solidity language.

6.3.2 Hyperledger Fabric

Hyperledger Fabric is a permissioned blockchain, hosted by Linux Foundation. It is used to accomplish distributed applications written in languages such as Go and Java. The smart contracts in Hyperledger Fabric are known as chain codes to execute the application logic automatically. Furthermore, consensus protocols, including Practical Byzantine Fault Tolerance (PBFT) and Raft are used and it has no fundamental cryptocurrency (Androulaki, et al., 2018).

6.3.3 EOS.IO

Enterprise Operating System (EOS) blockchain is designed to compete with the Ethereum blockchain framework. EOS is the first leading system that provides high throughput by Delegated Proof of Stake (DPoS) algorithm and uses in decentralized applications. The smart contract in EOSIO is written in C++ later on which complied through WebAssembly also known as Wasm (Huang, et al., 2020).

6.3.4 FISCO BCOS

Financial Blockchain Shenzhen Consortium (FISCO), a leading consortium blockchain, was founded by WeBank with the membership of Tencent and Huawei companies. FISCO is not a single blockchain. However, it is a unique blockchain application that is planned to benefit the general public. Additionally, it is a secure, portable blockchain and supports PBFT and Raft consensus algorithms (FISCO, 2020)

6.3.5 Corda

The R3 consortium created Corda as an open-source and permissioned blockchain framework in 2014. Corda underlines data privacy and follows the “Know Your Customer” term to share the transactions in the network. The smart contracts are written in Java and Kotlin language to support decentralized applications (Brown, 2018).

Table 7. Comparative analysis of blockchain deployment frameworks

Blockchain Framework	Category	Consensus algorithm	Smart contract Language	Hosted By	Cryptocurrency
Ethereum	Public	PoW	Solidity	Ethereum developers	Ether (ETH) and Bitcoin (BTC)
Hyperlegdger fabric	Private	PBFT	GoLang, Java	Linux Foundation	None
EOS.IO	Public and consortium	DPoS	C, C++	Block.One	EOS
FISCO BCOS	Consortium	PBFT, Raft	Solidity, C++	Webank	None
Corda	Consortium	PBFT, Raft	Kotlin, Java	R3 Consortium	None

7 Background and requirements for Swedish energy

7.1 SWEDISH ENERGY MARKETING

1) **Increasing electricity production and consumption**:

Electricity use in Sweden is expected to increase sharply until 2045, mainly due to the electrification of transport and industry. In several recently developed scenarios, electricity use will double by 2045 (Milton, et al., 2021). Renewable energy is increasing very quickly. Figure 6 shows the trend of installed electricity generation capacity in Sweden.

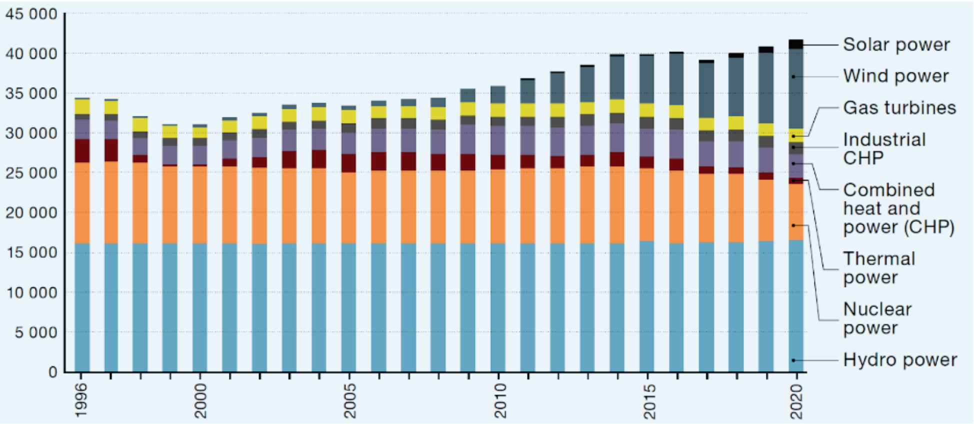


Figure 6. Installed electricity generation capacity by type of power 1996–2020, MW (Source: Swedenergy – Energiföretagen Sverige.)

2) **Layered architecture**:

Sweden's current electricity grid is usually divided into three levels; backbone network (transmission network), regional network, and local area network (distribution network).

3) **Lots of energy sectors**:

Approximately 170 electricity grid operators of different sizes are active in Sweden. There is only one electricity grid operator within each geographical area and the electricity consumer has no possibility of changing company. There are a few million stakeholders (electricity producers, distributors, electricity traders, electricity consumers, individual actors, and government agencies) in the energy business (including renewable energy).

4) **Free trading**:

In Sweden, trade in electricity is deregulated. You can decide who you want to purchase your electricity from as the client. However, electricity distribution via the electricity network takes place in a monopoly.

Electricity network operations in Sweden are therefore regulated by the Swedish Energy Markets Inspectorate (Ei).

5) **High digitalization**:

   The existing power system is highly digitalized, and many data readings are notified to the electronic system for direct processing, which is very conducive to the blockchain system to read the relevant data automatically. And the accuracy of data reading is relatively high.

6) **Separated energy sectors**:

   Lack of close collaboration between the energy sectors, in particular the collaboration between the renewable energy producers, and other energy producers.

7.2 SWEDISH CHALLENGES AND REQUIREMENTS FOR FUTURE ENERGY

1) Imbalances at different levels:
    a) Energy production, consumption, and storage under the dynamic scenarios. There is a need to maximize energy efficiency and minimize grid congestion.
    b) Dynamic frequency and voltage with renewable energy.
    c) Electricity quality is affected by the mixture of clean energy and dirty energy
    d) Different energy prices in different regions. Fair and easy trade is needed.
    e) Differences between the needs of individual energy producers and the global needs of the energy market.
    f) Imbalance at global and local levels and in between.
2) Business collaboration is limited between those renewable energy actors and various energy stakeholders. Data is not shared, and there are many silos of information. The integration should include planning, collaboration, and coordination.
3) A new legal proposal requires data on energy production and consumption to be available every 15 minutes. However, the existing system does not handle the analysis frequently enough, and some statistical frequencies are calculated on a longer period (hour, day, week, or annual basis).
4) Real-time monitoring is needed for both grid control and data report.
5) Energy storage (by a battery or a hydrogen gas) is needed to store unused renewable energy.

6) Since there is no competition in the electricity network market, the market must be regulated.
7) Consumers have a designation for the type of energy they consume.
8) Monitor and control the energy consumption of charging stations for electric vehicles.
9) Electricity quality control should extend to renewable energy producers; poisoned electricity should be controlled and regulated from the beginning.
10) Easier local trade and consumption of renewable energy. For example, the direct energy exchange between neighbors will improve energy efficiency.
11) Distinguish the boundary between technology and management. Such as data sharing should be controlled by related contracts, under uncertain situations.
12) Comply with and update laws and regulations to support new renewable energy development. To regulate renewable energy production with the grid capacity and ensure that the national/international regulations are intact.
13) Decentralization of power production is the future. However, it is also important to have plannable power to not lose competitiveness. The ideal is "A balanced, fossil-free power system with ⅓ base power, ⅓ control power, and ⅓ weather-dependent power evenly distributed geographically and with a high degree of utilization of the electricity grid (Milton, et al., 2021).
14) Good electricity, lots of electricity and electricity at the right time (Dagens Samhälle, 2021).

7.3 BLOCKCHAIN APPLICATION SCENARIOS

The Blockchain system is a software infrastructure built on top of the physical energy system (renewables and traditional power systems) that can enable various new applications.

The stakeholders of the Blockchain-based energy system can include energy producers, consumers, aggregators, grid owners, energy authorities, etc. While each stakeholder has their own interest and roles in the smart grid's production, distribution and control, blockchain technology can facilitate the data exchange between participants. Each stakeholder can contribute to the system by sharing data (information) to the Blockchain system while maintaining privacy and security. They can use the services (data, information, and applications) that the Blockchain can provide. The information provided via blockchain can help stakeholders improve their businesses accordingly.

Participation in the Blockchain is not mandatory. The Blockchain can only serve the participants who join and maintain it. Each participant has both responsibility for the Blockchain system and a benefit from it. For an idea model, if we hope that energy integration can cover as much as possible, the more stakeholders can participate, the better.

Some example scenarios:

1) **Energy integration**

   Each blockchain actor updates its generation, distribution, consumption and other figures in the blockchain. As a reward, each actor gets a global picture of the grid, e.g. how much energy is generated in a given period, how much is consumed in that period, etc. All actors can timely regulate their business, e.g., increase or decrease generation or consumption, change their business models, etc. Based on the available information and knowledge in the blockchain, the grid owners and operators can configure the infrastructure to adapt to the dynamic changes in electricity transmission and distribution. In the long run, all the available data and knowledge will help them update or redesign the infrastructure appropriately. Customers could be able to adapt their energy consumption for their different utilities that is based on their needs and market. Blockchain can, furthermore, support aggregators to identify inhouse consumption for different utilities, enabling automatic and up-to-date data to grid owners and producers. The energy authority can adapt regulations or issue new ones to manage and support flexible energy marketing on a large scale.

2) **Electric vehicle charging stations**

   When electric vehicle (EV) charging stations are integrated into a blockchain-based renewable energy system, as a stakeholder (consumer), each EV charging station automatically reports energy consumption to the blockchain so that the overall picture of the grid is shared to all participants, e.g., which charging station can available at a nearby location. The renewable energy sector can dynamically supply nearby charging stations based on real-time needs. This will not only benefit stakeholders (the renewable energy producers, grid owners, and aggregators), but also help drivers of electric vehicles to localize the suitable charging stations and optimize transportation locally and globally. Finally, it will improve energy efficiency.

3) **Free energy trading**

   Some channels can be freely built on the blockchain as subnets, and the members of the subgroups can directly exchange information and freely conduct business, such as energy trading, among themselves. This will allow these participants to create various new business models for energy marketing and enable fair and transparent marketing of energy trading. This model can be global (across the entire blockchain) or local (within a subnetwork of the blockchain). All players on the Blockchain will benefit from the integrated and free marketing model to optimize their business.

> Since the Blockchain provides a flexible, secure, reliable and robust software infrastructure, many potential applications and business models can be developed based on the Blockchain system. Of course, electrical engineering and appropriate technologies should support direct integration between the physical power system.

7.4 RECOMMENDATIONS IN SWEDEN

The energy blockchain system may provide potential new application scenarios for future energy applications, as well as new solutions for energy conservation and optimization. However, the development of large-scale blockchain real-world applications is still subject to the coupling challenge of technology and real-world systems. Therefore, the regional small-scale pilot implementation scenario experiment system will be very helpful to study the core technology and implementation scheme of the integration of the blockchain system and the energy system. As a continuation of this project, we plan to study the implementation of blockchain in the field of renewable energy. The goal here is to develop and test blockchain technology for the production, distribution and control of the renewable energy sector in southern Sweden. We hope to develop follow-up research projects in cooperation with Energiforsk and Energimyndigheten.

8 Conclusions

Blockchain-based smart grid systems can be executed independently and automatically according to certain predefined consensus mechanisms without human intervention, brokers, or central authorization, and enable efficient data aggregation techniques to solve privacy and security problems in the grid. This paper systematically explores blockchain-based applications for the management, control, and operation of smart grid systems. The paper focuses on non-financial applications of blockchain in the energy sector and divides the challenges into five main categories: Stakeholder Collaboration, Grid Imbalance, Data Management and Operations, Decentralization of Grid Operations, and Security and Privacy. Based on the review, analysis, and comparison with existing reviews the paper identifies additional challenges and highlights future research directions in the five categories.

Although the concept of blockchain is still most often associated with cryptocurrencies such as Bitcoin, it has been highlighted in theoretical and practical experiments in many contexts and sectors. One of the most important aspects of implementing a blockchain system is in the energy sector. Blockchain and related technologies are needed to handle the demand for decentralized applications and services in global renewable energy innovation. Blockchain can effectively deal with some of the key issues facing the renewable energy landscape, such as the contradiction between a large number of decentralized energy producers and drastically changing energy demand, coping with complex cross-system energy flows, balancing and transaction security, minimizing the environmental risks caused by energy use, and dealing with the demand for sustainable structures and the demand for greater flexibility.

Due to data encryption, accountability, and adaptability, there are also some system drawbacks and technical disadvantages. The relative novelty of the concept manifests itself in technical challenges, many of which have been solved, at least in principle. In general, the concept of blockchain for energy sectors is very attractive for the future. Still, the solution to the system challenges largely depends on key social and technological trends, the current and future power driving factors, and overall trends and constraints in the operation of the system. To influence these journeys, the academic and practical supporters of blockchain energy must combine further research and development with practical and real-life applications to demonstrate the real benefits and performance of the concept to relevant stakeholders and policymakers. Especially consider the concept of "design security" from a technology and IT perspective. In applying blockchain to energy sectors, cybersecurity cannot be ignored.

Existing technologies leverage different blockchain architectures for different application scenarios and demonstrate that the technology can be used to support smart grid infrastructure management and operations. However, actual implementations of the technology for grid management, control, and operations presented in the literature are still sporadic and localized. There is a lack of systematic technologies for smart grid management, control, and operation. This requires deconstruction of the existing grid management, control and operation, and systematic planning, design, and development of the corresponding blockchain application system by combining the technical advantages of blockchain. Since it is difficult to update the architecture of the blockchain system and the online storage of data is very long-lived, it is necessary to have a very clear understanding of the structure, business, and technical management of the existing power grid. Detailed prior knowledge of the future business and commercial expansion of the smart grid and a relatively clear prediction of the system technology and business trends are essential factors to design and develop a highly reliable, scalable, long-lived, and open blockchain system.

9 References

Aderibole, A., Aljarwan, A., Rehman, M. H. U., Zeineldin, H. H., Mezher, T., Salah, K., Salah, Damiani, E., & Svetinovic, D. (2020). Blockchain technology for smart grids: Decentralized NIST conceptual model. IEEE Access, 8, 43177-43190.

Adetokun, B. B., Muriithi, C. M., & Ojo, J. O. (2020). Voltage stability assessment and enhancement of power grid with increasing wind energy penetration. International Journal of Electrical Power & Energy Systems, 120, 105988.

Aggarwal, S., Kumar, N., Tanwar, S., & Alazab, M. (2021). A Survey on Energy Trading in the Smart Grid: Taxonomy, Research Challenges and Solutions. IEEE Access, 9, 116231-116253.

Ajadi, T., Cuming, V., Boyle, R., Strahan, D., Kimmel, M., Logan, M., & McCrone, A. (2020). Global trends in renewable energy investment 2020.

Alam, M. S., Al-Ismail, F. S., Salem, A., & Abido, M. A. (2020). High-level penetration of renewable energy sources into grid utility: Challenges and solutions. IEEE Access, 8, 190277-190299.

Aklilu, Y. T., & Ding, J. (2021). Survey on blockchain for smart grid management, control, and operation. Energies, 15(1), 193.

Alladi, T., Chamola, V., Rodrigues, J. J., & Kozlov, S. A. (2019). Blockchain in smart grids: A review on different use cases. Sensors, 19(22), 4862.

Alt, R., & Wende, E. (2020). Blockchain technology in energy markets–An interview with the European Energy Exchange. Electronic Markets, 30(2), 325-330.

Andoni, M., Robu, V., Flynn, D., Abram, S., Geach, D., Jenkins, D., ... & Peacock, A. (2019). Blockchain technology in the energy sector: A systematic review of challenges and opportunities. Renewable and Sustainable Energy Reviews, 100, 143-174.

E. Androulaki, A. Barger, V. Bortnikov, C. Cachin, K. Christidis, A. D. Caro, D. Enyeart, C. Ferris, G. Laventman, Y. Manevich, S. Muralidharan, C. Murthy, B. Nguyen, M. Sethi, G. Singh, K. Smith, A. Sorniotti, C. Stathakopoulou, M. Vukolić, S. W. Cocco and J. Yellick, "Hyperledger fabric," in Proceedings of the Thirteenth EuroSys Conference, 2018.

Ante, L., Steinmetz, F., & Fiedler, I. (2021). Blockchain and energy: A bibliometric analysis and review. Renewable and Sustainable Energy Reviews, 137, 110597.

Asija, D., & Viral, R. (2021). Renewable energy integration in modern deregulated power system: challenges, driving forces, and lessons for future road map. In Advances in Smart Grid Power System (pp. 365-384). Academic Press.

Badal, F.R., Das, P., Sarker, S.K. and Das, S.K., (2019). A survey on control issues in renewable energy integration and microgrid. Protection and Control of Modern Power Systems, 4(1), p.8.

Bajaj, M., & Singh, A. K. (2020). Grid integrated renewable DG systems: A review of power quality challenges and state-of-the-art mitigation techniques. International Journal of Energy Research, 44(1), 26-69.

Baliga, A. (2017). Understanding blockchain consensus models. Persistent, 4, 1-14.

Bamakan, S. M. H., Motavali, A., & Bondarti, A. B. (2020). A survey of blockchain consensus algorithms performance evaluation criteria. Expert Systems with Applications, 154, 113385.

Bao, J., He, D., Luo, M., & Choo, K. K. R. (2020). A survey of blockchain applications in the energy sector. IEEE Systems Journal.

Bergquist, J., Laszka, A., Sturm, M., & Dubey, A. (2017, December). On the design of communication and transaction anonymity in blockchain-based transactive microgrids. In Proceedings of the 1st Workshop on Scalable and Resilient Infrastructures for Distributed Ledgers (pp. 1-6)

Brilliantova, V., & Thurner, T. W. (2019). Blockchain and the future of energy. Technology in Society, 57, 38-45.

Brooklyn. BMG (2019). Brooklyn Energy. [Accessed on 2021-11-23 at https://www.brooklyn.energy/]

R. G. Brown, "The corda platform: An introduction," 2018.

Buterin, V. "A next generation smart contract & decentralized application platform," 2013.

Byfield, S., & Vetter, D. (2016). Flexibility concepts for the German power supply in 2050: Ensuring stability in the age of renewable energies. Acatech–Deutsche Akademie der Technikwissenschaften: Munich, Germany.

Casado-Vara, R., Prieto, J., & Corchado, J. M. (2018, June). How blockchain could improve fraud detection in power distribution grid. In The 13th International Conference on Soft Computing Models in Industrial and Environmental Applications (pp. 67-76). Springer, Cham.

Cash, M., & Bassiouni, M. (2018, September). Two-tier permission-ed and permission-less blockchain for secure data sharing. In 2018 IEEE International Conference on Smart Cloud (SmartCloud) (pp. 138-144). IEEE.

Casino, F., Dasaklis, T. K., & Patsakis, C. (2019). A systematic literature review of blockchain-based applications: current status, classification and open issues. Telematics and informatics, 36, 55-81.

Castro, M., & Liskov, B. (1999, February). Practical byzantine fault tolerance. In OSDI (Vol. 99, No. 1999, pp. 173-186).

Chen, H., Wang, X., Li, Z., Chen, W., & Cai, Y. (2019). Distributed sensing and cooperative estimation/detection of ubiquitous power internet of things. Protection and Control of Modern Power Systems, 4(1), 1-8.

Cheng, S., Zeng, B. and Huang, Y.Z., (2017), November. Research on application models of blockchain technology in the distributed electricity market. In IOP Conference Series: Earth and Environmental Science (Vol. 93, No. 1, p. 012065). IOP Publishing.

Choudhury, S. (2020). A comprehensive review on issues, investigations, control and protection trends, technical challenges and future directions for Microgrid technology. International Transactions on Electrical Energy Systems, 30(9), e12446.

Cioara, T., Antal, M., Mihailescu, V. T., Antal, C. D., Anghel, I. M., & Mitrea, D. (2021). Blockchain-Based Decentralized Virtual Power Plants of Small Prosumers. IEEE Access, 9, 29490-29504.

Cioara, T., Pop, C., Zanc, R., Anghel, I., Antal, M., & Salomie, I. (2020, December). Smart Grid Management using Blockchain: Future Scenarios and Challenges. In 2020 19th RoEduNet Conference: Networking in Education and Research (RoEduNet) (pp. 1-5). IEEE.

Clack, C. D., Bakshi, V. A., & Braine, L. (2016). Smart contract templates: foundations, design landscape and research directions. arXiv preprint arXiv:1608.00771.

Cole, W., & Frazier, A. W. (2018). Impacts of increasing penetration of renewable energy on the operation of the power sector. The Electricity Journal, 31(10), 24-31. Faizan, M., Brenner, T., Foerster, F., Wittwer, C., & Koch, B. (2019). Decentralized bottom-up energy trading using Ethereum as a platform. Journal of Energy Markets, 12(2).

Dagens Samhälle (2021), Dod el, mycket el och el I rätten tid, Debatt (Available on 20220427 at https://www.dagenssamhalle.se/opinion/debatt/god-el-mycket-el-och-el-i-rattan-tid/

Danzi, P., Angjelichinoski, M., Stefanovic, C., & Popovski, P. (2017, October). Distributed proportional-fairness control in microgrids via blockchain smart contracts. In 2017 IEEE International Conference on Smart Grid Communications (SmartGridComm) (pp. 45-51). IEEE.

Davis, S. J., Lewis, N. S., Shaner, M., Aggarwal, S., Arent, D., Azevedo, I. L., ... & Caldeira, K. (2018). Net-zero emissions energy systems. Science, 360(6396).

DeCusatis, C., & Lotay, K. (2018, August). Secure, decentralized energy resource management using the ethereum blockchain. In 2018 17th IEEE International Conference On Trust, Security And Privacy In Computing And Communications/12th IEEE International Conference On Big Data Science And Engineering (TrustCom/BigDataSE) (pp. 1907-1913). IEEE.

Dib, O., Brousmiche, K. L., Durand, A., Thea, E., & Hamida, E. B. (2018). Consortium blockchains: Overview, applications and challenges. International Journal On Advances in Telecommunications, 11(1&2), 51-64.

Ding, J. & Naserinia, V. (2022). Blockchain for future renewable energy, to appear in the book: Decentralized Frameworks for Future Power systems -Operation, Planning and Control Perspectives, Edited by Mohsen Parsa Moghaddam, Reza Zamani, Hassan Haes Alhelou, and Pierluigi Siano, Academic Press, 2022. ISBN-13: 978-0323916981.

Di Silvestre, M. L., Gallo, P., Guerrero, J. M., Musca, R., Sanseverino, E. R., Sciumè, G., ... & Zizzo, G. (2020). Blockchain for power systems: Current trends and future applications. Renewable and Sustainable Energy Reviews, 119, 109585.

Dong, Z., Luo, F., & Liang, G. (2018). Blockchain: a secure, decentralized, trusted cyber infrastructure solution for future energy systems. Journal of Modern Power Systems and Clean Energy, 6(5), 958-967.

Electron. (2020). Electron. Lounch and Operate Distributed Energy Markets. [Accessed on 2021-11-23 at https://electron.net/]

El Mrabet, Z., Kaabouch, N., El Ghazi, H., & El Ghazi, H. (2018). Cyber-security in smart grid: Survey and challenges. Computers & Electrical Engineering, 67, 469-482.

Energimyndigheten (2020). [Accessed on 2021-11-23 at https://www.energimyndigheten.se/statistik/den-officiellastatistiken/statistikprodukter/natanslutna-solcellsanlaggningar/]

Engebretson, P. (2013). The basics of hacking and penetration testing: ethical hacking and penetration testing made easy. Elsevier.

European Commission (EU) (2015), Energy Union Package, A framework strategy for a resilient energy union with a forward-looking climate change policy, Brussels, [Access on 20211026 at https://www.eea.europa.eu/policy-documents/com-2015-80-final]

Faisal, M. A., Aung, Z., Williams, J. R., & Sanchez, A. (2014). Data-stream-based intrusion detection system for advanced metering infrastructure in smart grid: A feasibility study. IEEE Systems journal, 9(1), 31-44.

Fan, M., & Zhang, X. (2019). Consortium blockchain based data aggregation and regulation mechanism for smart grid. IEEE Access, 7, 35929-35940.

Ferdous, M. S., Chowdhury, M. J. M., & Hoque, M. A. (2021). A survey of consensus algorithms in public blockchain systems for crypto-currencies. Journal of Network and Computer Applications, 103035.

FISCO BCOS. Fisco bcos: Challenging hyperledger fabric with a consortium chain from china. 2018. URL: https://www.prnewswire.com/news-releases/fisco-bcos-challenging-hyperledger-fabric-with-a-consortium-chain-from-china-300733474.html .

Foti, M., & Vavalis, M. (2021). What blockchain can do for power grids?. Blockchain: Research and Applications, 100008.

Frost, R., Zieland, L., Sharafi, D., & Susanto, J. (2020, November). Impact of Reverse Power Flow in Distribution Feeders on Under-Frequency Load Shedding Schemes. In 2020 International Conference on Smart Grids and Energy Systems (SGES) (pp. 100-104). IEEE.

Fu, X., Wang, H. & Shi, P. (2021).A survey of Blockchain consensus algorithms: mechanism, design and applications. Sci. China Inf. Sci. 64, 121101.

Gai, K., Wu, Y., Zhu, L., Xu, L., & Zhang, Y. (2019). Permissioned blockchain and edge computing empowered privacy-preserving smart grid networks. IEEE Internet of Things Journal, 6(5), 7992-8004.

Galici, M., Mureddu, M., Ghiani, E., Celli, G., Pilo, F., Porcu, P., & Canetto, B. (2021). Energy Blockchain for Public Energy Communities. Applied Sciences, 11(8), 3457.

Gao, J., Asamoah, K. O., Sifah, E. B., Smahi, A., Xia, Q., Xia, H., ... & Dong, G. (2018). GridMonitoring: Secured sovereign blockchain based monitoring on smart grid. IEEE Access, 6, 9917-9925.

Guan, Z., Si, G., Zhang, X., Wu, L., Guizani, N., Du, X., & Ma, Y. (2018). Privacy-preserving and efficient aggregation based on blockchain for power grid communications in smart communities. IEEE Communications Magazine, 56(7), 82-88.

Hamouda, M. R., Nassar, M. E., & Salama, M. M. A. (2020). A Novel Energy Trading Framework Using Adapted Blockchain Technology. IEEE Transactions on Smart Grid, 12(3), 2165-2175.

Hannan, M. A., Tan, S. Y., Al-Shetwi, A. Q., Jern, K. P., & Begum, R. A. (2020). Optimized controller for renewable energy sources integration into microgrid: Functions, constraints and suggestions. Journal of Cleaner Production, 256, 120419.

Hassan, M. U., Rehmani, M. H., & Chen, J. (2019). DEAL: Differentially private auction for blockchain-based microgrids energy trading. IEEE Transactions on Services Computing, 13(2), 263-275.

Hasse, F., Von Perfall, A., Hillebrand, T., Smole, E., Lay, L., & Charlet, M. (2016). Blockchain–an opportunity for energy producers and consumers. PwC global power & utilities, 1-45.

Hasankhani, A., Hakimi, S. M., Bisheh-Niasar, M., Shafie-khah, M., & Asadolahi, H. (2021). Blockchain technology in the future smart grids: A comprehensive review and frameworks. International Journal of Electrical Power & Energy Systems, 129, 106811.

Heck, K., Mengelkamp, E., & Weinhardt, C. (2021). Blockchain-based local energy markets: Decentralized trading on single-board computers. Energy Systems, 12(3), 603-618.

Hodge, B. M. S., Jain, H., Brancucci, C., Seo, G. S., Korpås, M., Kiviluoma, J., ... & Kroposki, B. (2020). Addressing technical challenges in 100% variable inverter-based renewable energy power systems. Wiley Interdisciplinary Reviews: Energy and Environment, 9(5), e376.

J. P. Holguin, D. C. Rodriguez and G. Ramos, "Reverse Power Flow (RPF) Detection and Impact on Protection Coordination of Distribution Systems," in IEEE Transactions on Industry Applications, vol. 56, no. 3, pp. 2393-2401, May-June 2020, doi: 10.1109/TIA.2020.2969640.

Hu, B., Zhou, C., Tian, Y. C., Hu, X., & Junping, X. (2020). Decentralized consensus decision-making for cybersecurity protection in multimicrogrid systems. IEEE Transactions on Systems, Man, and Cybernetics: Systems, 51(4), 2187-2198.

Y. Huang, H. Wang, L. Wu, G. Tyson, X. Luo, R. Zhang, X. Liu, G. Huang and X. Jiang, "Characterizing EOSIO Blockchain," arXiv preprint arXiv:2002.05369, 2020.

Hussain, S. S., Farooq, S. M., & Ustun, T. S. (2019, March). Implementation of blockchain technology for energy trading with smart meters. In 2019 Innovations in Power and Advanced Computing Technologies (i-PACT) (Vol. 1, pp. 1-5). IEEE.

Impram, S., Nese, S. V., & Oral, B. (2020). Challenges of renewable energy penetration on power system flexibility: A survey. Energy Strategy Reviews, 31, 100539.

Leander, C.K. and M. (2021). Renewable Energy in the Nordics 2021, Nordic Energy Research. Nordic Energy Research.

Khalid, R., Javaid, N., Almogren, A., Javed, M. U., Javaid, S., & Zuair, M. (2020). A blockchain-based load balancing in decentralized hybrid P2P energy trading market in smart grid. IEEE Access, 8, 47047-47062.

Kamal, M., & Tariq, M. (2019). Light-weight security and blockchain based provenance for advanced metering infrastructure. IEEE Access, 7, 87345-87356.

Kappagantu, R., & Daniel, S. A. (2018). Challenges and issues of smart grid implementation: A case of Indian scenario. Journal of Electrical Systems and Information Technology, 5(3), 453-467.

Kimani, K., Oduol, V., & Langat, K. (2019). Cyber security challenges for IoT-based smart grid networks. International Journal of Critical Infrastructure Protection, 25, 36-49.

Knirsch, F., Brunner, C., Unterweger, A., & Engel, D. (2020). Decentralized and permission-less green energy certificates with GECKO. Energy Informatics, 3(1), 1-17.

Kong, X., Zhang, J., Wang, H., & Shu, J. (2019). Decentralized multi-chain data management framework for power systems. CSEE Journal of Power and Energy Systems (JPES), 1.

Kumari, A., Gupta, R., Tanwar, S., Tyagi, S., & Kumar, N. (2020). When blockchain meets smart grid: Secure energy trading in demand response management. IEEE Network, 34(5), 299-305.

Konashevych, O. I. (2016). Advantages and current issues of blockchain use in microgrids. ISSN 0204–3572. Electronic Modeling. 2016. V. 38. No 2.

Kuznetsova, E., Cardin, M. A., Diao, M., & Zhang, S. (2019). Integrated decision-support methodology for combined centralized-decentralized waste-to-energy management systems design. Renewable and Sustainable Energy Reviews, 103, 477-500.

Kumar, P., Lin, Y., Bai, G., Paverd, A., Dong, J. S., & Martin, A. (2019). Smart grid metering networks: A survey on security, privacy and open research issues. IEEE Communications Surveys & Tutorials, 21(3), 2886-2927.

Lamport, L., Shostak, R., & Pease, M. (2019). The Byzantine generals problem. In Concurrency: the Works of Leslie Lamport (pp. 203-226).

Laszka, A., Dubey, A., Walker, M., & Schmidt, D. (2017, October). Providing privacy, safety, and security in IoT-based transactive energy systems using distributed ledgers. In Proceedings of the Seventh International Conference on the Internet of Things (pp. 1-8).

Li, Z., Bahramirad, S., Paaso, A., Yan, M., & Shahidehpour, M. (2019a). Blockchain for decentralized transactive energy management system in networked microgrids. The Electricity Journal, 32(4), 58-72.

Li, Y., Teng, Y., Cao, R., & Li, N. (2019b). Research on Coordination Control Systems of Virtual Power Plant Based on Blockchain. In 2019 IEEE 8th International Conference on Advanced Power System Automation and Protection (APAP) (pp. 1377-1383). IEEE.

Li, J., Zhou, Z., Wu, J., Li, J., Mumtaz, S., Lin, X., ... & Alotaibi, S. (2019c). Decentralized on-demand energy supply for blockchain in Internet of Things: A microgrids approach. IEEE transactions on computational social systems, 6(6), 1395-1406.

Li, Y., Yang, W., He, P., Chen, C., Wang, X., (2019d). Design and management of a distributed hybrid energy system through smart contract and blockchain. Appl. Energy 248, 390–405.

Liang, S. H. E. N., Baozhong, H. A. O., Yang, L. I., Han, Y. U., Song, Z. H. A. N. G., Hao, M. E. N., & Jingang, F. A. N. (2020, November). Blockchain-based Power Grid Data Asset Management Architecture. In 2020 International Conference on Computer Science and Management Technology (ICCSMT) (pp. 207-211). IEEE.

Liang, G., Weller, S. R., Luo, F., Zhao, J., & Dong, Z. Y. (2018). Distributed blockchain-based data protection framework for modern power systems against cyber attacks. IEEE Transactions on Smart Grid, 10(3), 3162-3173.

Liu, C., Zhang, X., Chai, K. K., Loo, J., & Chen, Y. (2021). A survey on blockchain-enabled smart grids: Advances, applications and challenges. IET Smart Cities, 3(2), 56-78.

Luo, X., Xue, K., Xu, J., Sun, Q., & Zhang, Y. (2021). Blockchain Based Secure Data Aggregation and Distributed Power Dispatching for Microgrids. IEEE Transactions on Smart Grid.

Madhu, G. M., Vyjayanthi, C., & Modi, C. N. (2019). A Novel Framework for Monitoring Solar PV based Electric Vehicle Community Charging Station and Grid Frequency Regulation using Blockchain. In 2019 10th International Conference on Computing, Communication and Networking Technologies (ICCCNT) (pp. 1-7). IEEE.

G. C. Mahato, T. R. Choudhury, B. Nayak, D. Debnath, S. B. Santra and B. Misra, "A Review on High PV Penetration on Smart Grid: Challenges and its Mitigation using FPPT," 2021 1st International Conference on Power Electronics and Energy (ICPEE), 2021, pp. 1-6, doi: 10.1109/ICPEE50452.2021.9358474.

Mattila, J. (2016). The blockchain phenomenon–the disruptive potential of distributed consensus architectures (No. 38). ETLA working papers.

Mattila, J., Seppälä, T., Naucler, C., Stahl, R., Tikkanen, M., Bådenlid, A., & Seppälä, J. (2016). Industrial blockchain platforms: An exercise in use case development in the energy industry (No. 43). ETLA Working Papers.

Mazzola, L., Denzler, A., & Christen, R. (2020). Towards a Peer-to-Peer Energy Market: an Overview. arXiv preprint arXiv:2003.07940.

Mingxiao, D., Xiaofeng, M., Zhe, Z., Xiangwei, W. and Qijun, C., 2017, October. A review on consensus algorithm of blockchain. In 2017 IEEE international conference on systems, man, and cybernetics (SMC) (pp. 2567-2572). IEEE.

Mnatsakanyan, A., Albeshr, H., Al Marzooqi, A., & Bilbao, E. (2020, September). Blockchain-Integrated Virtual Power Plant Demonstration. In 2020 2nd International Conference on Smart Power & Internet Energy Systems (SPIES) (pp. 172-175). IEEE.

Mollah, M.B., Zhao, J., Niyato, D., Lam, K.Y., Zhang, X., Ghias, A.M., Koh, L.H. and Yang, L., (2020). Blockchain for future smart grid: A comprehensive survey. IEEE Internet of Things Journal, 8(1), pp.18-43.

Musleh, A. S., Yao, G., & Muyeen, S. M. (2019). Blockchain applications in smart grid–review and frameworks. Ieee Access, 7, 86746-86757.

Mylrea, M. (2019). Distributed autonomous energy organizations: next-generation blockchain applications for energy infrastructure. In Artificial Intelligence for the Internet of Everything (pp. 217-239). Academic Press.

Nakamoto, S. (2008). Bitcoin: A peer-to-peer electronic cash system. Decentralized Business Review, 21260.

Nurgaliev, A. S., Vershinin, I. S., & Minyazev, R. S. (2019, March). Concept and implementation of blockchain demonstration unit within the smart grid. In 2019 International Conference on Industrial Engineering, Applications and Manufacturing (ICIEAM) (pp. 1-6). IEEE.

Olivares-Rojas, J. C., Reyes-Archundia, E., Gutiérrez-Gnecchi, J. A., Cerda-Jacobo, J., & González-Murueta, J. W. (2019). A novel multitier blockchain architecture to protect data in smart metering systems. IEEE Transactions on Engineering Management, 67(4), 1271-1284.

Ourahou, M., Ayrir, W., Hassouni, B. E., & Haddi, A. (2020). Review on smart grid control and reliability in presence of renewable energies: Challenges and prospects. Mathematics and computers in simulation, 167, 19-31.

Patil, H., Sharma, S., & Raja, L. (2021). Study of blockchain based smart grid for energy optimization. Materials Today: Proceedings, 44, 4666-4670.

Peter, V., Paredes, J., Rivial, M. R., Sepúlveda, E. S., & Astorga, D. A. H. (2019). Blockchain meets Energy: Digital Solutions for a Decentralized and Decarbonized Sector. German-Mexican Energy Partnership (EP) and Florence School of Regulation (FSR), 1–45.

Pillitteri, V. and Brewer, T. (2014), Guidelines for Smart Grid Cybersecurity, NIST Interagency/Internal Report (NISTIR), National Institute of Standards and Technology, Gaithersburg, MD, [online], https://doi.org/10.6028/NIST.IR.7628r1 (Accessed September 17, 2021)

Rahmadika, S., Ramdania, D. R., & Harika, M. (2019). A Blockchain Approach for the Future Renewable Energy Transaction. In Journal of Physics: Conference Series (Vol. 1175, No. 1, p. 012122). IOP Publishing.

Rapier, E. (2017). From Yelp reviews to mango shipments: IBM’s CEO on how Blockchain will change the world. Reviewed from Business Insider.

Rhydwan, A. H. M., Choyon, M. M. S., Iftekhar, M. N., Sad, A. M. H., & Nandi, D. (2020, December). Smart Grid Implementation with Consortium Blockchain: A Proposed Model for Bangladesh. In 2020 Emerging Technology in Computing, Communication and Electronics (ETCCE) (pp. 1-6). IEEE.

Salkuti, S. R. (2020). Challenges, issues and opportunities for the development of smart grid. Int. J. Electr. Comput. Eng.(IJECE), 10, 1179-1186.

Samad, T., & Annaswamy, A. M. (2017). Controls for smart grids: Architectures and applications. Proceedings of the IEEE, 105(11), 2244-2261.

S. Samy, M. Azab and M. Rizk, "Towards a Secured Blockchain-based Smart Grid," 2021 IEEE 11th Annual Computing and Communication Workshop and Conference (CCWC), 2021, pp. 1066-1069, doi: 10.1109/CCWC51732.2021.9376089.

Shahidehpour, M., Yan, M., Shikhar, P., Bahramirad, S., & Paaso, A. (2020). Blockchain for Peer-to-Peer Transactive Energy Trading in Networked

Microgrids: Providing an Effective and Decentralized Strategy. IEEE Electrification Magazine, 8(4), 80-90.

Shahzad, Y., Javed, H., Farman, H., Ahmad, J., Jan, B., & Zubair, M. (2020). Internet of energy: Opportunities, applications, architectures and challenges in smart industries. Computers & Electrical Engineering, 86, 106739.

Sinsel, S. R., Riemke, R. L., & Hoffmann, V. H. (2020). Challenges and solution technologies for the integration of variable renewable energy sources—a review. renewable energy, 145, 2271-2285.

Soto, E. A., Bosman, L. B., Wollega, E., & Leon-Salas, W. D. (2020). Peer-to-peer energy trading: A review of the literature. Applied Energy, 116268.

Suciu, G., Sachian, M. A., Vochin, M., Dobrea, M., Beceanu, C., Iosu, R., & Petrache, A. (2019a). Blockchain applicability using Smart Power Management: SealedGrid Architecture. In 2019 IEEE PES Innovative Smart Grid Technologies Europe (Ismart gridT-Europe) (pp. 1-5). IEEE.

Suciu, G., Sachian, M. A., Dobrea, M., Istrate, C. I., Petrache, A. L., Vulpe, A., & Vochin, M. (2019b, September). Securing the smart grid: A blockchain-based secure smart energy system. In 2019 54th International Universities Power Engineering Conference (UPEC) (pp. 1-5). IEEE

Sun, H., Guo, Q., Qi, J., Ajjarapu, V., Bravo, R., Chow, J., ... & Yang, G. (2019). Review of challenges and research opportunities for voltage control in smart grids. IEEE Transactions on Power Systems, 34(4), 2790-2801.

Szabo, N. (1997). Formalizing and securing relationships on public networks. First monday.

Talat, R., Muzammal, M., Qu, Q., Zhou, W., Najam-ul-Islam, M., Bamakan, S. H., & Qiu, J. (2020). A decentralized system for green energy distribution in a smart grid. Journal of Energy Engineering, 146(1), 04019036.

Teufel, B., Sentic, A., & Barmet, M. (2019). Blockchain energy: Blockchain in future energy systems. Journal of Electronic Science and Technology, 17(4), 100011. Tveten, Å. G. (2020). Renewable energy in Northern European power markets: effects, challenges and integration options, PhD Thesis.

Triantafyllou, A., Jimenez, J. A. P., Torres, A. D. R., Lagkas, T., Rantos, K., & Sarigiannidis, P. (2020). The challenges of privacy and access control as key perspectives for the future electric smart grid. IEEE Open Journal of the Communications Society, 1, 1934-1960.

Tschorsch, F., & Scheuermann, B. (2016). Bitcoin and beyond: A technical survey on decentralized digital currencies. IEEE Communications Surveys & Tutorials, 18(3), 2084-2123.

Unahalekhaka, P., & Sripakarach, P. (2020). Reduction of reverse power flow using the appropriate size and installation position of a BESS for a PV power plant. IEEE Access, 8, 102897-102906.

Wang, Q., & Su, M. (2020). Integrating blockchain technology into the energy sector—from theory of blockchain to research and application of energy blockchain. Computer Science Review, 37, 100275.

Wood, G. (2017). Ethereum: a secure decentralised generalised transaction ledger (2014).

Wu, Y., Wu, Y., Guerrero, J. M., & Vasquez, J. C. (2021). Digitalization and decentralization driving transactive energy Internet: Key technologies and infrastructures. International Journal of Electrical Power & Energy Systems, 126, 106593.

Xie, J., Tang, H., Huang, T., Yu, F. R., Xie, R., Liu, J., & Liu, Y. (2019). A survey of blockchain technology applied to smart cities: Research issues and challenges. IEEE Communications Surveys & Tutorials, 21(3), 2794-2830.

Xue, L., Teng, Y., Zhang, Z., Li, J., Wang, K., & Huang, Q. (2017, September). Blockchain technology for electricity market in microgrid. In 2017 2nd International Conference on Power and Renewable Energy (ICPRE) (pp. 704-708). IEEE.

Yaga, D., Mell, P., Roby, N., & Scarfone, K. (2019). Blockchain technology overview. arXiv preprint arXiv:1906.11078.

Yapa, C., de Alwis, C., Liyanage, M., & Ekanayake, J. (2021). Survey on blockchain for future smart grids: Technical aspects, applications, integration challenges and future research. Energy Reports, 7, 6530-6564.

Yang, Q., Wang, H., Wang, T., Zhang, S., Wu, X., & Wang, H. (2021). Blockchain-based decentralized energy management platform for residential distributed energy resources in a virtual power plant. Applied Energy, 294, 117026.

Yao, Y., Gao, C., Chen, T., Yang, J., & Chen, S. (2021). Distributed electric energy trading model and strategy analysis based on prospect theory. International Journal of Electrical Power & Energy Systems, 131, 106865.

Yuan, Y., & Wang, F. Y. (2016). Blockchain: the state of the art and future trends. Acta Automatica Sinica, 42(4), 481-494.

Zhang, H., Wang, J., & Ding, Y. (2019). Blockchain-based decentralized and secure keyless signature scheme for smart grid. Energy, 180, 955-967.

Zhao, Z., Guo, J., Luo, X., Xue, J., Lai, C. S., Xu, Z., & Lai, L. L. (2020). Energy transaction for multi-microgrids and internal microgrid based on blockchain. IEEE Access, 8, 144362-144372.

Zhou, Y., Guan, Y., Zhang, Z., & Li, F. (2019, October). A blockchain-based access control scheme for smart grids. In 2019 International Conference on Networking and Network Applications (NaNA) (pp. 368-373). IEEE.

Zhu, S., Song, M., Lim, M. K., Wang, J., & Zhao, J. (2020). The development of energy blockchain and its implications for China's energy sector. Resources Policy, 66, 101595.

Zhuang, P., Zamir, T., & Liang, H. (2020). Blockchain for cybersecurity in smart grid: A comprehensive survey. IEEE Transactions on Industrial Informatics, 17(1), 3-19.

Zia, M. F., Benbouzid, M., Elbouchikhi, E., Muyeen, S. M., Techato, K., & Guerrero, J. M. (2020). Microgrid transactive energy: Review, architectures, distributed ledger technologies, and market analysis. Ieee Access, 8, 19410-19432.

Zimmermann, H., & Hoppe, J. (2018). Blockchain–Opportunities and threats for the energy transition.

BLOCKCHAIN FOR SMART GRID OPERATIONS, CONTROL, AND MANAGEMENT

A comprehensive overview of blockchain-based smart grid management, control, and operation solutions. The report compares with related reviews and highlights the challenges in management, control, and operation for a blockchain-based smart grid, as well as future research directions in five categories: collaboration between actors, data analytics and management, control of network imbalances, decentralization of network management and operation, security and privacy.

The report reviews how blockchain technology can potentially solve the challenges of decentralized solutions for future renewable energy systems. As a result, several applications of blockchain for renewable energy are discussed, such as electric vehicles, decentralized P2P energy transactions, carbon certification and trading, physical information security, energy transfer, Energy-to-X, and the Internet of Energy.

A guideline for the implementation of blockchain to corresponding applications for future renewable energy is also presented in this report. This includes the different blockchain system architectures, the data flow from the power grid processed and recorded, the choice of the appropriate consensus, and the different blockchain frameworks.

Energiforsk is the Swedish Energy Research Centre – an industrially owned body dedicated to meeting the common energy challenges faced by industries, authorities and society. Our vision is to be hub of Swedish energy research and our mission is to make the world of energy smarter!

Energiforsk