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# Sustainable Electrification—Advances and Challenges in Electrical-Distribution Networks: A Review

**Jimmy Gallegos, Paul Arévalo *, Christian Montaleza and Francisco Jurado**

Department of Electrical Engineering, EPS Linares, University of Jaén, 23700 Jaén, Spain; jwga0001@red.ujaen.es (J.G.); cimg0001@red.ujaen.es (C.M.); fjurado@ujaen.es (F.J.)
* Correspondence: warevalo@ujaen.es

**Abstract:** This paper provides a thorough exploration of the evolution and contemporary trends in electrical-distribution networks, with a focus on smart grids in the context of Industry 4.0. Beginning with the traditional components of electrical grids, the study highlights the transition towards sustainable energy sources and the integration of renewables. Key trends include economic operation, the application of distributed energy resources, and the significance of photovoltaic solar energy. The paper unfolds in seven sections, examining smart-electrical-network architecture, sustainable technology progression, energy efficiency, carbon-emission-reduction challenges, future perspectives, and concluding insights. Each section delves into specific layers and aspects, such as data management, electrical infrastructure, automation, and consumer interaction. The intricate role of smart meters and their impact on energy management is explored, providing a comprehensive overview of the current state and future directions of electrical-distribution networks.

**Keywords:** electrical-distribution network; renewable energy sources; Industry 4.0; efficiency; cybersecurity

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## 1. Introduction

In the present era, the world is increasingly interconnected through new technological advancements that have revolutionized and shifted paradigms in various sectors such as transportation, telecommunications, and the electrical industry. The objective is to enhance the efficiency of each sector. The advent of the Fourth Industrial Revolution facilitates real-time data exchange among a diverse array of intelligent meters for various purposes, enabling the integration of smart grids with Industry 4.0. This integration leads to more efficient and sustainable industrial processes, improved energy management, and cost savings. This review focuses on the electrical sector, particularly on smart grid systems, economic trends, the quality of energy distribution, and current challenges. The starting point is conventional electrical grids, typically comprising three main components: generation, transmission, and distribution. The first aspect under consideration is the generation component, which involves the production of electrical energy from various sources, including fossil fuels, nuclear energy, and renewable sources [1].

The rise in global demand for electrical energy, coupled with the energy crisis triggered by the depletion of fossil resources, climate change, and environmental preservation concerns, has led to the evolution of electrical distribution in a logical manner. This evolution has had considerable effects on aspects such as the design, analysis, and construction of the electrical grid, as well as its operations and maintenance [2]. Electricity stands out as a primary product derived from the use of fossil fuels, resulting in significant consequences such as air pollution stemming from thermal convergence [1]. Additionally, conventional energy distribution experiences line losses and voltage deviations due to the constant growth in energy demand [3]. Therefore, the optimization of controllable loads using intelligent distribution techniques becomes imperative, yielding outcomes such as cost reduction, energy efficiency, and enhanced environmental management and safety [4].

Progress in electric-generation technology introduces new engineering methods and experimentation to address the energy deficit, with renewable energy sources (RESs) emerging as a viable alternative [5]. This shift prompted the United Nations to set clear objectives for 2030, aiming to ensure clean and sustainable energy [6]. In 2020, the major contributors were hydropower with 1190 GW, followed by wind energy with 623 GW, solar energy providing 586 GW, biomass contributing 14 GW, and geothermal energy making a 500 MW contribution [4]. However, the challenge remains in generating energy even under unpredictable climatic conditions [7]. One of the most significant trends in distribution networks is economic operation and network optimization. By analyzing historical economic data and various factors, the aim is to identify potential opportunities for energy savings and loss reduction in the electrical network [8]. This approach can assist utility companies in optimizing their operations and enhancing the overall efficiency of the distribution network. The first trend involves the application of distributed energy resources (DERs), reminiscent of synchronous generators. However, with the rise of advanced technology, energy-storage systems and smart grids are being developed to address new challenges and enable the efficient integration of RESs [9].

The integration of RESs, such as distributed generators (DGs), stands as another crucial trend in distribution networks. The introduction of DGs aims to reduce transmission losses and increase the share of RESs to enhance efficiency. Studies predict that the proportion of global energy consumption from RESs will reach around 80% by 2050. This trend necessitates the development of advanced protection and stability-assessment techniques to ensure the reliable and safe operation of the network [10]. Continuing with emerging trends is photovoltaic solar energy (PV), which holds the potential to drive a sustainable future as a renewable and clean energy source. Efforts have been made to improve the distribution of wind and PV energy in integrated assessment models through smart grids, supercapacitors, or the use and control of microgrids [11]. PV solar energy has been recognized as a key component of sustainable development in various countries [12,13]. Similarly, the importance of education and research in solar energy for sustainable energy development has been emphasized [14], as it has the potential to achieve energy goals contributing to the development of net-zero-energy buildings, thereby avoiding the generation of greenhouse gases and other significant environmental impacts [12]. Key aspects include front–end AC/DC converters, power-smoothing technology, bidirectional communication standards, proactive self-healing, advanced technology in smart homes, artificial intelligence techniques, and the integration of electric vehicles (EVs).

This article is organized into seven sections. In Section 2, the architecture of smart electrical networks based on renewable sources is described. Section 3 delves into the progression of sustainable technology in electrical-distribution networks. Section 4 focuses on energy efficiency and the quality of energy distribution. Section 5 explores the reduction of carbon emissions and the associated challenges. Section 6 introduces discussions and provides insights into future perspectives. Finally, Section 7 presents the conclusions derived from the preceding sections.

## 2. Architecture of Smart Electrical Networks Based on Renewable Sources

Smart grids are advanced electrical systems that integrate information and communication technology to enhance the efficiency, reliability, and sustainability of electrical-energy distribution. These networks are typically organized into multiple layers to manage various aspects of the infrastructure. Each layer plays a crucial role in the operation and enhancement of the smart grid. In Figure 1, each of these layers is described, providing a general overview of how they are organized within a smart electrical grid. This structure is divided into six layers: data management, electrical infrastructure, automation and control, consumer interaction, communication, and security.

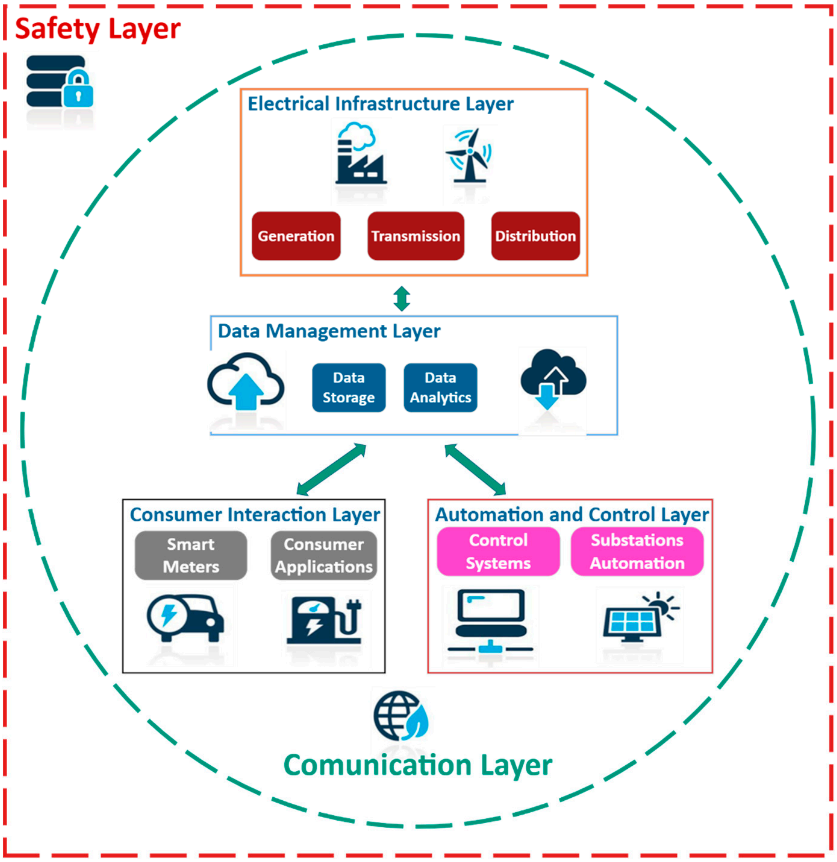


**Figure 1.** General diagram of the six layers of the smart electrical grid.

## 2.1. Data-Management Layer

This layer is responsible for processing and managing big data across various domains, including smart homes [15], smart grids [16], smart cities [17], and healthcare. In the context of smart homes, a layered architecture for big data processing and management is proposed [15]. This architecture consists of multiple layers, including a data-management and -visualization layer, which is tasked with handling the collection, storage, and visualization of data [18]. Furthermore, an integrated framework for big data management and analysis is required to efficiently enable real-time data control and management, as demonstrated in the research study [19].

In Figure 2, it is observed that the communication layer exchanges information passively across all layers through a bidirectional flow of energy and data. This flow extends from energy generation, through the transmission and distribution network, to the energy consumer, utilizing tools such as big data for data management, blockchain for energy trading among prosumers, and data usage [20,21]. The significance of efficient big data analytics in the smart grid is crucial as it can prevent economic, social, and technical losses under unfavorable conditions [22].


**Figure 2.** Bidirectional flow of information data in smart grid.

### 2.2. Electrical-Infrastructure Layer

This layer encompasses power-generation plants, such as power stations, wind farms, and PV plants. When utilizing RESs, their unpredictable nature, such as wind speed, must be considered. For instance, wind farms, as a source of renewable energy, have been subject to numerous studies in different contexts. In Europe, there has been an analysis of the impact of wind turbines on the electrical grid and the regulatory framework for wind farms [23]. Furthermore, the importance of evolving infrastructure for connecting offshore wind farms to the centralized onshore grid has been emphasized [24].

On the other hand, in Brazil, challenges have been highlighted in locating regions with reliable winds for wind farm implementation due to the scarcity of valid data ensuring park efficiency [25]. Concerning the establishment of wind farms, the significance of various stages, including determining the installation site, assessing local wind potential, identifying wind power, and predicting wind power generation, has been underscored [26]. Moreover, research has delved into the economic feasibility of wind energy hybrid systems linked to the power grid, emphasizing the critical role of economic factors in the development of wind farms [27]. In Table 1, wind farms play a significant role in specific geographical areas, exhibiting variations in both their geographical location and design. For example, the Alta Wind Energy Center, situated in California, is an expansive onshore facility comprising over 600 turbines. This facility stands among the largest globally, possessing a total capacity of 1548 MW. In contrast, Sheringham Shoal, located in the North Sea, is an offshore wind farm featuring 88 turbines with a capacity of 317 MW. The distinction lies in the park type, with Alta Wind Energy Center being onshore, while Sheringham Shoal operates offshore. Environmental assessments have been conducted by the parks to understand and minimize their impact. The Alta Wind Energy Center significantly contributes to California's grid, while Sheringham Shoal has been pivotal in renewable energy generation in the UK. The turbine technology also differs, with onshore turbines in Alta Wind Energy Center and offshore turbines in Sheringham Shoal. The parks are operational, with inaugurations between 2010 and 2015 for the Alta Wind Energy Center and in 2012 for Sheringham Shoal.

**Table 1.** Wind farms' comparison.

| Aspect | Alta Wind Energy Center, USA | Sheringham Shoal, UK |
|---|---|---|
| **Location capacity type** | California, USA 1548 MW onshore | North Sea, off Norfolk, UK 317 MW offshore |
| **Number of turbines Operator** | Over 600 turbines (multiple phases) NRG Energy | 88 turbines equinor (formerly Statoil) |
| **Inauguration** | Phases between 2010 and 2015 | 2012 |
| **Grid Connection** | Connects to California's grid | Connects to the UK's national grid |
| **Environmental-impact studies** | Conducted | Conducted |
| **Technology** | Land-based turbines | Offshore wind turbines |
| **Significance** | One of the largest onshore wind farms | Significant contribution to UK's offshore wind capacity |
| **Economic viability Studies** | No specific information available | No specific information available |
| **Infrastructure** | Transmission infrastructure for grid connection | Submarine connections and transformation stations |

These wind farms represent significant advancements in renewable energy generation, contributing uniquely to their respective regions: Alta Wind Energy Center on land extension and Sheringham Shoal in marine expansion. In Figure 3, two blocks are depicted. The first block is the energy-transmission block, responsible for transporting electricity over long distances through high-voltage lines. The second block enables distribution, delivering electricity to end users through substations and distribution lines [28]. This layer is interconnected through various layers such as the communication layer, the consumer-interaction layer, the automation and control layer, and the data-management layer to prevent energy losses, maintain a self-healing network, and analyze data to detect cybersecurity threats against electrical systems that could have physical impacts on the electrical layer [29].

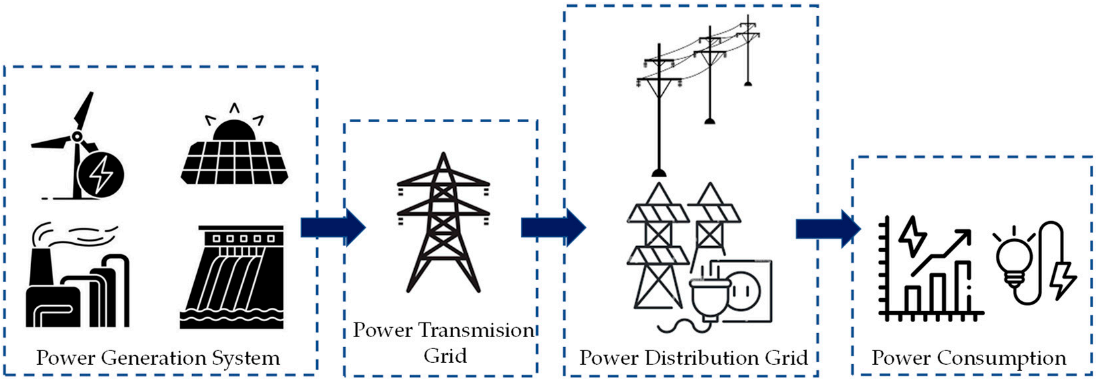


**Figure 3.** Flow diagram of electrical distribution.

### *2.3. Automation and Control Layer*

#### 2.3.1. Power-System Optimization and Supply–Demand Analytics

To optimize smart grid power systems, predictive models are needed for demand forecasting and supply and demand analysis, and optimization techniques have been widely used to address the challenges of integrating uncertain renewable energy sources. Power-system deregulation and random-load fluctuations, methods used to predict the volatility of financial markets, can also be used to predict the volatility of environmental and load demands highlighting the importance of predictive modeling in this context [30].

Demand management and economic-performance optimization require the application of machine-learning algorithms to identify consumers with similar lifestyles based on their daily energy consumption. Forecasting, fault diagnosis, maintenance, operation planning, sizing, and risk management require the deployment of Bayesian networks for probabilistic modeling of uncertain components of a power system [31].

To schedule smart meter devices and optimize demand-response approaches, it is necessary to develop incentive-based demand-response strategies, together with reliable load-forecasting techniques based on classical statistics or AI and machine learning. These strategies are critical to increasing the technical and economic efficiency of the smart grid, making them an essential part of power-system optimization.

#### 2.3.2. Power-System Automation in Electrical Networks

Automation in the smart grid is a crucial aspect of modern-electrical-network infrastructure. It involves the integration of advanced technology such as automation systems, communication protocols, and control functions to enhance the efficiency, reliability, and security of the network [30]. One key component of automation in the smart grid is the implementation of control functions. Systems-control engineering plays a fundamental role in designing and optimizing control strategies for smart grid applications [31]. These control functions enable the network to dynamically respond to changes in electricity demand and supply, ensuring efficient and reliable operation.

To maximize the utilization of local resources and enhance the efficiency of energy-management systems, microgrids are employed [32]. A study explores different types of microgrid control systems via IoT, SCADA monitoring, and cloud computing [33]. Microgrids are not the only case of automation and control. In the context of battery-energy-storage systems, control-based smoothing approaches have been proposed to optimize state of charge and prevent overcharging or discharging [34].

Automation in the smart grid, within the context of Industry 4.0, has become a topic of great relevance. The Spanish Domotics Association defines intelligent automation as the use of technology to efficiently manage energy usage, provide security and comfort, and enable communication between the user and the system [35]. This intelligent automation has extended to manufacturing industries, involving the interconnection of sensitive parts of businesses to improve adaptability through artificial intelligence (AI) processes [36].

The integration of cyber–physical systems in industrial automation has been a topic of interest, with the application of cyber–physical production systems (CPPSs) enabling access to innovative functionalities based on network connectivity and Internet access [37]. The importance of infrastructure evolution for connecting offshore wind farms to the centralized onshore grid has also been emphasized, highlighting the relevance of automation in electricity generation from renewable sources [24].

In the realm of industrial automation, the impact of new technology such as intelligent big data and cloud computing has been assessed [38]. These technological advances have contributed to the efficiency, flexibility, and adaptability of production systems, underscoring the importance of intelligent automation in the context of Industry 4.0. Automation in the smart grid, under the Industry 4.0 framework, spans from intelligent home automation to the integration of cyber–physical systems in the industry, transforming how energy resources are managed and production processes are optimized. Table 2 demonstrates that the automation of electrical networks not only improves operational efficiency but also establishes the foundation for a more sustainable and resilient network capable of effectively addressing future energy challenges.

**Table 2.** Power grid automation technology.

| Technology | Description | Benefits |
|---|---|---|
| Advanced Metering Infrastructure (AMI) | Utilizes smart meters for real-time-consumption monitoring | - Remote reading<br>- Early detection of problems<br>- Implementation of dynamic tariffs |
| Supervisory Control and Data Acquisition (SCADA) | Monitor and control equipment in real time | - Improves visibility and control<br>- Facilitates real-time decision making |
| Substation Automation | Uses automated systems and devices | - Improved network reliability<br>- Reduced response time to failures<br>- More efficient operations |
| Smart Grids | Integrates technology to optimize network | - Improved energy efficiency<br>- Integration of renewable sources<br>- Improved demand response |
| Energy-Storage Systems with Automatic Control | Uses batteries to store and release power | - Improved grid stability<br>- Efficient management of intermittent renewable energy |
| Predictive Analytics and Maintenance | Uses algorithms to anticipate failures and proactive maintenance | - Reduced downtime<br>- Prolongation of equipment service life |
| Advanced Protection Systems | Use advanced protection devices | - Improved safety and reliability<br>- Fast and accurate fault detection and isolation |
| IoT Integration | Connects devices and sensors on the network | - Advanced monitoring and control<br>- Decision making based on real-time information |

A rapidly growing field of research and development is the integration of IoT devices into the electrical network, with applications ranging from enhancing power quality to optimizing renewable energy generation and network operational efficiency. The incorporation of IoT (Internet of Things) devices into the electrical grid stands as an exceptionally pertinent subject in contemporary times. The transformative impact of IoT devices, capable of gathering and transmitting real-time data, has revolutionized the monitoring, control, and management of the electrical network. The deployment of IoT devices within the electrical network facilitates a more intricate monitoring of aspects such as energy demand, distributed generation, service quality, and operational efficiency. The academic literature has addressed the integration of IoT devices into the electrical network from various perspectives. For instance, it has been demonstrated that a multilevel inverter D-STATCOM can reduce total harmonic distortion in electrical-distribution systems with nonlinear loads [39]. This type of device exemplifies the application of advanced technology to improve power quality in the electrical network.

Furthermore, a detailed analysis of the PV and wind energy supply system has been conducted, considering its dependence on the electrical grid. This study emphasizes the importance of understanding how renewable energy systems, integrated with IoT devices, interact with the existing electrical network [40]. On the other hand, a pre-feasibility study of a hybrid wind and $H_2$ energy system connected to the electrical grid has been carried out. This type of research demonstrates how integrating IoT devices into renewable energy generation can have significant economic implications, highlighting the importance of economic considerations in the development of IoT-connected energy systems [27].

These methodologies employ fuzzy control mechanisms and low-pass filters to regulate the charging or discharging power, guaranteeing the battery's operation within secure thresholds. The control administration involving supercapacitors within smart grids represents a developing field of investigation with the goal of enhancing the efficiency and functionality of supercapacitors within the realm of smart grid applications. Supercapacitors, identified as energy-storage devices, possess the capability to store and release substantial amounts of energy rapidly. They exhibit characteristics such as high power density, swift charging and discharging capabilities, and extended life cycles [41,42]. One potential application of supercapacitors in smart grids is as backup power sources or uninterruptible power systems. Supercapacitors can provide additional power during peak demand periods or in case of outages, ensuring a stable and reliable power supply [43]. This can contribute to improving the overall resilience and reliability of the smart grid system.

### 2.4. Consumer-Interaction Layer

Consumer-interaction layer is characterized by the integration of hardware and computational intelligence to monitor, control, and manage energy generation, distribution, storage, and consumption through smart meters [44]. To understand the role of smart meters in energy management, it is crucial to consider the existing academic literature on the subject. For example, a comprehensive review has been conducted on the data analytics of smart meters, highlighting applications, methodologies, and associated challenges [45]. This study provides an overview of the various applications and methodological approaches used in smart meter data analytics, underscoring the importance of this technology in energy management. Moreover, the availability of datasets such as the UK-DALE dataset, providing electricity-demand data at the appliance and whole-house levels from five UK households, has allowed significant advances in understanding household energy consumption [46]. This type of data is essential for comprehending energy-consumption behavior and optimizing its management through smart meters.

In Table 3, a considerable number of providers in the market is evident, and the mentioned companies serve as illustrative examples. The selection of a smart meter implementer relies on the specific requirements of the electrical grid and the energy efficiency objectives of the entity. Additionally, the research underscores the significance of technological advancements in managing electric energy generated by off-grid PV systems, emphasizing the imperative need for intelligent measurement systems for efficient energy management [47]. Moreover, a study has been conducted on the data intelligence of smart meters for future energy systems, highlighting the importance of computational intelligence in energy management [48]. However, user acceptance and participation in the smart grid depend on their perception of its reliability [49], as well as the functions and interactions of users with other stakeholders. The market and technological advancements must be assessed for a comprehensive understanding of the development of smart grids, particularly in the residential sector [50].

**Table 3.** Smart-meter-development companies.

| Technology | Description | Benefits |
|---|---|---|
| **Itron** | Leading in technology and services for energy management. | Advanced meters, communication, and data management. |
| **Landis + Gyr** | Global provider of solutions for intelligent energy management. | Advanced meters, communication systems, and analytics. |
| **Schneider Electric** | Offers comprehensive solutions for energy efficiency. | Smart meters, energy-management systems. |
| **Siemens** | Global-technology-solutions provider. | Smart meters, energy-management platforms. |
| **Kamstrup** | Specialized in intelligent metering solutions. | Smart meters for electricity, water, and heating. |
| **Elster (Honeywell)** | Provides advanced metering solutions. | Smart meters and communication systems. |
| **Sensus (Xylem)** | Offers advanced metering solutions. | Smart meters and communication systems. |
| **Holley Technology** | Specializes in smart metering solutions. | Smart meters and energy-management systems. |
| **Kromschroeder (IDEX)** | Provides intelligent metering solutions. | Smart meters, including gas meters. |

### 2.5. Communication Layer

The communication layer facilitates bidirectional communication between the utility company and energy consumers through the transmission of data among devices, sensors, and systems across the entire network [51]. This ensures the security and reliability of communication in smart grid environments. In the study [52] it was determined that sharing dynamic states among power system generators is crucial for wide-area monitoring, decentralized control, and the protection of the future smart grid. However, this sharing process is subject to cyber–physical contingency conditions, limiting its precision. Figure 4 incorporates a cyber layer with the electrical system to guarantee the precise exchange of dynamic states of generators. The proposed framework utilizes a weighted-average consensus mechanism within a blockchain environment [52].

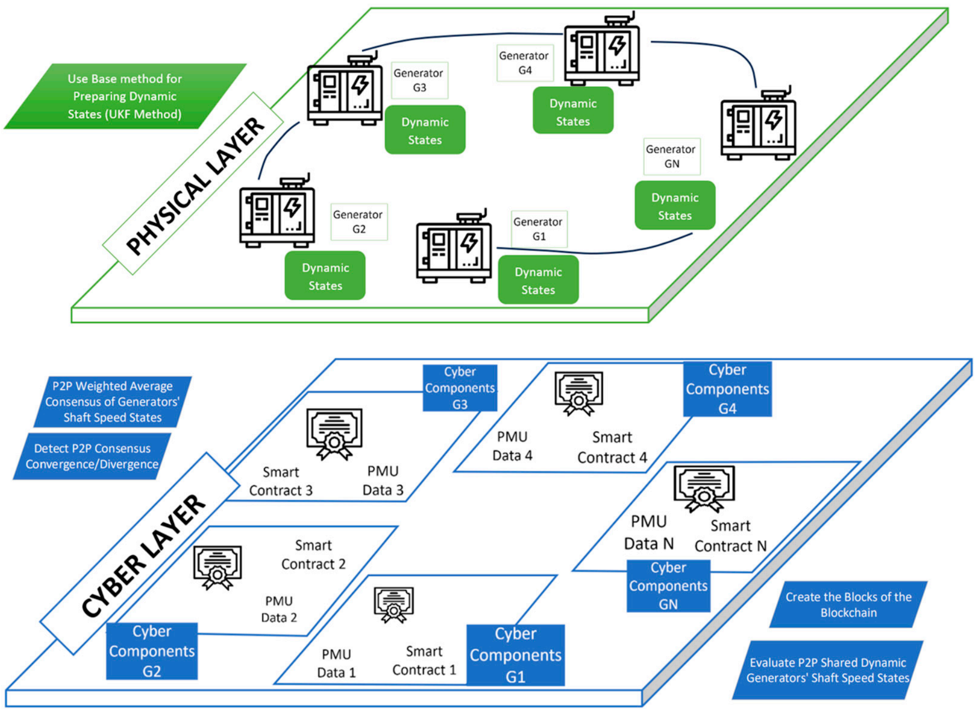


**Figure 4.** Description of the physical layer and digital-layer diagram.

In a recent study [53], a transmission/reception system is proposed for data communication in a smart grid, using optimal orthogonal frequency division multiplexing (OFDM). The performance of a transmission channel with high-, medium-, and low-voltage power lines is considered Class A noise, composed of Gaussian noise and impulsive noise. Digital data is transmitted through the transmitter, passes through the Class A noise channel, and is received at the receiver, where OFDM performance estimation is conducted. The bit error rate (BER) is obtained by comparing transmitted and received bits and calculating the number of incorrectly received bits. This is completed for each signal-to-noise-ratio (SNR) value, starting at zero decibels and increasing by two decibels. The tabulated values are then used to create BER versus SNR graphs [53].

### *2.6. Security Layer*

It is one of the most important aspects of smart grid systems due to their increased vulnerability to cyber threats [54]. The functionality of a smart grid heavily relies on cyber communication. To address the cybersecurity issues of smart grid systems, research has been conducted focusing on various aspects, such as intrusion-detection systems (IDSs), which play an essential role in protecting smart grid systems [55]. A common cyberattack on smart grids is the injection of false data, which distorts the measurements collected by the system operator [56]. Proactive identification of security threats is achieved through the development of formal security-verification techniques that uncover cybersecurity and physical-security threats in different components of smart grid systems.

The smart grid is described as a dynamic and interactive infrastructure that integrates millions of energy devices and sensors, enabling rapid transmission, monitoring, and bidirectional energy management through advanced communication systems and smart meters. Overall, the architecture of a smart grid is a multifaceted and hierarchical system that requires careful consideration of control, communication, security, and flexibility to ensure its efficient and reliable operation.

## **3. Advancement of Sustainable Technology in Electrical-Distribution Grids**

The advancement in electrical-distribution networks is occurring through the implementation of innovative technology that enable smart grids to automate the supply and distribution of energy, allowing for a higher level of connectivity in the distribution network. The smart grid integrates various technologies, such as self-charging power units, AI, the IoT, blockchain, and machine learning, to optimize the efficiency, reliability, and sustainability of energy distribution.

### *3.1. Self-Charging Power Unit*

The use of ambient energy serves as an alternative to energy-storage devices; however, no matter how high the energy density, batteries will eventually discharge. Therefore, a novel approach involves integrating an energy-harvesting system, current-control circuitry, and an energy-storage device into a self-discharge battery, essentially creating a self-charging power unit (SCPU) that benefits from continuous harvesting. The energy-management system ensures that the generated energy is stored with maximum efficiency, and the energy-storage unit should act as a "reserve" that regulates the collected energy for controlled output. The resulting energy is used to manage the output, as depicted in Figure 5. In this case, the battery density does not necessarily need to be very high, but it can operate sustainably [57], utilizing triboelectric nanogenerators (TEN), as mentioned in [58].

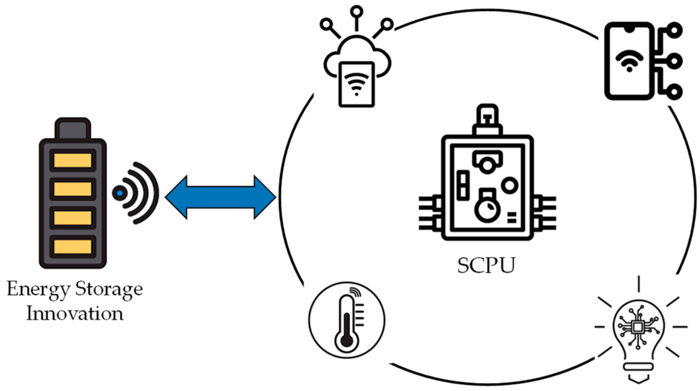


**Figure 5.** Self-charging energy-storage units provide controlled production to the prosumer.

### 3.2. Internet of Things

Bidirectional internet and communication technologies facilitate successful energy trading, transforming physical entities into intelligent devices that collect, communicate, control, and interpret real-time environmental information, as illustrated in Figure 6. This ushers in a new perspective for the distributed energy market, incorporating healthier network monitoring and control, asset management, data security, and privacy measures, ultimately enhancing system reliability and efficiency. Moreover, the transition to smart grids involves utilizing the distributed electricity market in a regulated manner, underscoring the importance of regulatory standards and policies to ensure the profitability of the intelligent distribution network [59]. The parameters and the structure of smart meters within a smart grid are detailed in [60].

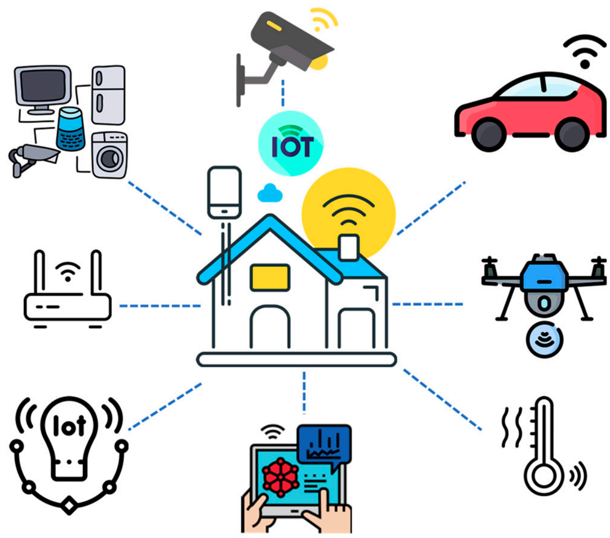


**Figure 6.** Smart home using IoT.

### 3.3. Blockchain

Blockchain technology has garnered significant attention in the energy sector, particularly within the context of smart grids (see Figure 7). It provides a promising solution to enhance the security and resilience of smart grids, enabling secure and efficient energy transactions while addressing issues of trust and security [61,62]. Moreover, nearly 20% of decision makers believe that blockchain technology will be a primary technology in smart grids, underscoring its potential impact [63]. In this review, a case study of Brooklyn (NY, USA) MicroGrid was found, representing a blockchain-based peer-to-peer (P2P) energy-trading platform managed by Transactive Grid, a partnership between LO3Energy, Consensys, Siemens, and Centrica.

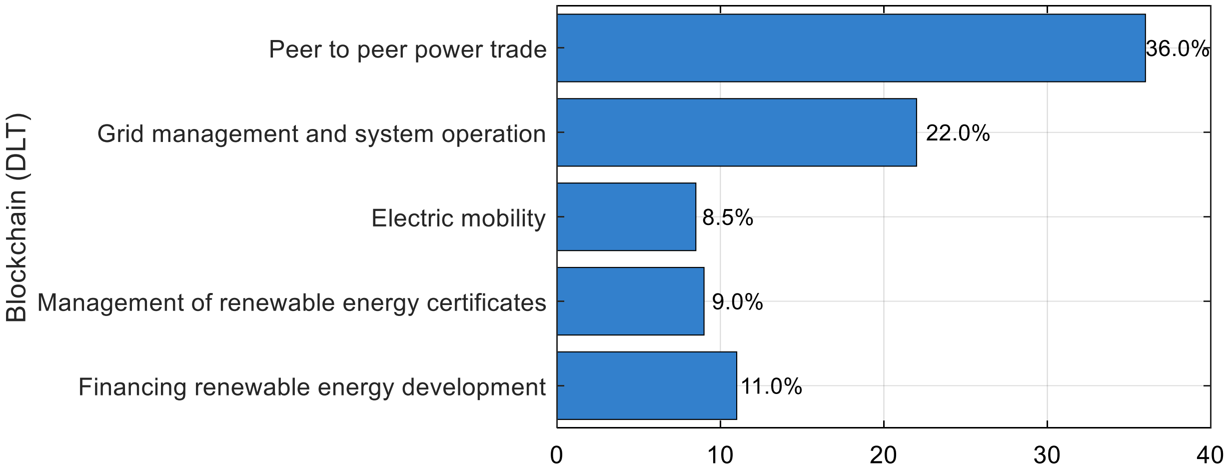


**Figure 7.** Smart contracts applying blockchain technology for the power system.

The application of blockchain in smart grids involves various-use cases, including smart energy metering, energy trading, and data aggregation. It offers a secure and resilient framework for smart grid security, protecting against cyberattacks and ensuring system integrity and confidentiality [64]. Additionally, the performance of blockchain technology in smart grids has been analyzed, with studies conducting performance analyses using Ethereum and Hyperledger Fabric-based implementations, demonstrating its viability and potential benefits [65].

The potential of blockchain technology in smart grids extends to its role in improving energy efficiency, providing a decentralized and secure platform for energy management, and contributing to the intelligent and transparent operation of the energy system [62]. Furthermore, the application of blockchain in smart grids aligns with the broader trend of leveraging information and communication technology to revolutionize the energy landscape, offering long-term opportunities to make the energy system more efficient and secure [62].

### *3.4. Fault Location, Isolation, and Service Restoration*

Designated as FLISR, it is a critical aspect of modern smart grid systems aimed at achieving self-healing capabilities and enhancing the reliability of energy-distribution networks [66]. The successful implementation of FLISR (fault location, isolation, and service restoration) applications on advanced platforms such as GridAPPS-D has demonstrated the potential to adopt new and advanced ADMSs (advanced distribution-management systems) applications to support future energy-distribution systems [67]. Leveraging modern software technology alongside existing network infrastructure has shown benefits for both network management and operations, in addition to enhancing service quality for customers [68]. Furthermore, the concept of smart grids emphasizes the importance of intelligent protection and measurement devices, reliable data communication, optimal energy-management systems, and fault detection, location, isolation, and restoration (FLISR) for distribution grids [66]. The significance of FLISR is further underscored by its role in the reliability and resilience of smart grids. Proactive self-healing, a fundamental feature of smart grids, is closely linked to the successful implementation of FLISR. Moreover, the reliability analysis of protection systems in smart grids emphasizes the formal assessment of protection systems, including FLISR, to ensure the reliability of smart grid operations [69].

### *3.5. Artificial Intelligence and Virtual Power Plants*

Incorporating AI into virtual power plants (VPPs) within smart grids is essential for optimizing the integration of distributed energy resources, the electric grid, controllable loads, and EVs. The VPP concept is evolving to address climate change challenges and ensure the effective utilization of renewable energy within the electric grid [70]. Understanding the dimensions and factors influencing the integration of small-scale sources into VPP structures within the smart grid is crucial [71].

As illustrated in Figure 8, the integration of renewable energy into the grid through VPPs provides enhanced operational flexibility, albeit with additional capital costs for control systems and software [70]. VPPs represent an innovative concept that aggregates small, distributed energy resources, acting as a unified conventional power plant in the electricity market. The smart grid, as the next-generation electric network, employs bidirectional flows of electricity and information to establish an automated, widely distributed energy-supply network. AI plays a significant technological role in smart grids, and its applications can boost and enhance the reliability and resilience of smart grid systems [4]. Smart grids can be defined as the integration of electrical networks, communication networks, specific hardware, and computational intelligence to monitor, control, and manage the generation, distribution, storage, and consumption of energy [44].

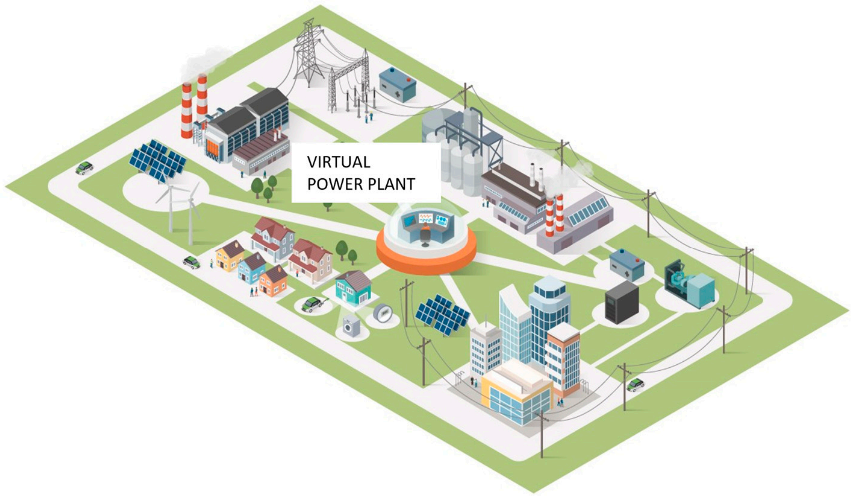


**Figure 8.** Virtual power plant into smart grid.

### *3.6. Robustness in Electrical-Distribution Networks*

The robustness of electrical-distribution networks is critical in determining the reliability and quality of the electrical supply, addressing key parameters such as line loadability, system redundancy, intermittency of renewable sources, and recovery capacity after a failure, especially in networks predominantly composed of renewable sources, which, lacking rotational inertia, can induce instability in the main electrical grid [72]. The literature review reveals significant advances in improving the efficiency and resilience of critical infrastructures, such as electrical-distribution networks and water-supply systems. In study [72], a network-partition method based on the Monte Carlo algorithm and spectral clustering optimization is proposed. This approach tackles congestion and computational complexity issues associated with data centralization in the cloud, emphasizing its application in configuring peripheral servers for edge computing. Furthermore, validation on real electrical-network models shows substantial improvements in accuracy and robustness compared to traditional methods. Another study [73] proposes a network-reduction methodology based on the generalized Thevenin theorem, addressing optimization and reorganization of existing networks by connecting subnetworks. The research emphasizes the importance of considering uncertainties in the reconfiguration of distribution networks to enhance their robustness and operational efficiency.

Another study [74] focuses on strategies to enhance resilience in electrical networks with multiple energy sources. The proposal to subdivide the network into stable and sustainable subnetworks, identify key nodes, and establish attack and repair strategies based on the resilience cycle highlights the importance of understanding fault propagation and network-recovery capacity. Quantitative evaluation in an enhanced IEEE 118 bus system underscores the effectiveness of these strategies, providing valuable insights to strengthen the defense and resilience of electrical networks. In the realm of reverse logistics, a robustness-measurement methodology based on information theory is proposed and adapted from measurements in electrical systems [75]. Its application in a case study of pallet and large-bag recovery demonstrates the efficiency of the methodology, classifying solutions based on their robustness in different scenarios. The proportional relationship between facility capacity and system robustness underscores the importance of considering these metrics in supply chain design, with practical implications for logistical decision making.

Finally, the study [76] investigates the robustness of electrical networks incorporating renewable energy sources. The focus on the interval electrical-betweenness metric highlights critical nodes and the vulnerability of networks. However, the application of attack strategies based on this metric shows significant damage in renewable energy networks. The research emphasizes the need to carefully consider the implications of integrating renewable energy sources in the planning and operation of electrical networks [76]. Therefore, researchers emphasize the development of new methods to address the challenges of large-scale penetration of renewable sources, especially in non-robust systems. One significant challenge is the effective management of variability and intermittency associated with sources like solar and wind as power-smoothing techniques. The accurate prediction of production and implementation of advanced storage technology are crucial to address fluctuations in energy supply and ensure a constant supply. Additionally, the integration of distributed generation systems and adaptation to the growing complexity of the network will be crucial to maintain the dynamic stability of the electrical system. The control system must ensure that production and demand are as closely matched as possible at all times.

Another major challenge is the detection and classification of extreme events and faults in the network. Designing efficient recovery strategies and implementing technology that allows rapid service restoration are critical aspects to ensure the continuity of electrical supply in adverse situations. Furthermore, cybersecurity emerges as a growing challenge, given the increased connectivity in smart grids, requiring robust measures to protect against potential threats and attacks. The need for reconfiguration and modernization of existing infrastructure is also a significant challenge. The integration of emerging technologies, such as artificial intelligence and the Internet of Things, into the management and operation of electrical networks will demand considerable investments and a planned transition to avoid significant disruptions in supply. Moreover, coordination and international standardization will become essential aspects, especially in the context of the growing interconnection of electrical networks globally. The establishment of common standards will facilitate interoperability and efficient energy management on an international scale.

## 4. Integration of Energy Storage and Management Systems into Electrical-Distribution Networks

### *4.1. Supercapacitors*

To enhance energy quality and mitigate fluctuations, addressing key sources of disturbances affecting the quality of electrical services and quantifying the severity of these disturbances is crucial. Customized energy devices and systems based on supercapacitors or flywheels can be employed to mitigate voltage drops and improve energy quality in distribution networks [41]. Additionally, the use of inverters in hybrid energy systems, such as those combining PV and grid power, can significantly enhance the quality of supplied electrical energy [43]. Sustainable-energy-development implementation is essential to meet the growing energy demand while preserving environmental quality and natural resources. Studies and measurements analyzing energy-quality parameters like waveform distortions (harmonics), voltage fluctuations, and power factor are important to provide recommendations for maintaining equipment's proper operation.

A study in [77] proposes that voltage drop is a crucial component of electrical quality for distribution-network operation. In the past, superconducting magnetic energy storage (SMES) with a predetermined capacity was used to mitigate voltage drop. A weighted sum of voltage drops and SMES cost is used to reduce a developed multi-objective function. Fuzzy logic controller (FLC)–SMES sizing and multi-objective function weighting factors are optimized using the Mountain Gazelle Optimizer (MGO), a novel optimization technique. The implementation of Karot, a real electric-distribution network in Egypt supplying power to 16 induction irrigation motors and residential loads, is a case study to demonstrate the performance of the ideal FLC–SMES mitigation strategy for voltage drop. Particle Swarm Optimization (PSO) compares results obtained with those determined to validate the performance of the MGO technique. Current results show that the SMES unit optimized using MGO, with a capacity of 0.135 MJ and an actual cost of 0.2483 M$, successfully mitigated the voltage sag in the investigated network by simultaneously starting the irrigation motors, where voltage never dropped below 0.9 p.u. compared to the 0.625 MJ capacity and 0.6934 M$ actual cost of the non-optimized SMES unit. This indicates a 78% decrease in capacity and a 64% decrease in the actual cost of the SMES unit, respectively.

Supercapacitors have emerged as a promising technology to enhance energy quality in smart grids. They offer rapid charge/discharge rates, high power density, and excellent cyclic stability, making them suitable for applications like backup power, uninterrupted power supply, and high-power assistance in smart grids [42]. In China, a Double-Layer Supercapacitor, Faraday Pseudocapacitor, and Hybrid Supercapacitor have been implemented, representing 38.2% and 30.8% in supercapacitor consumption in transportation and industry, with new energy accounting for 21.8%, and equipment and other applications representing 9.2% [78].

*4.2. Hydrogen-Storage System*

The global transition to renewable energy sources and the electrification of various sectors demand innovative solutions to enhance the efficiency and resilience of electrical-distribution networks. This section provides an analysis centered around the integration of hydrogen within the context of electric-distribution systems. In the study conducted by [79], challenges associated with distributed generation and the intermittency of renewable energy sources are addressed. The proposal focuses on collaborative solutions involving energy storage, highlighting the crucial role of hydrogen fuel cells. The proposed correlation between storage technology and ancillary services aims to encourage prosumer participation, underscoring the importance of effective regulatory frameworks. The work presented in [80] assesses the financial risk of a smart grid with high penetration of photovoltaic systems and hydrogen-powered vehicles. Using a scenario-based approach and a downside risk-constraint methodology, the study concludes that hydrogen technology can effectively mitigate economic risks associated with photovoltaic-penetrated distribution networks.

The proposal in [81] introduces a data-driven methodology to model energy and hydrogen generation from sustainable energy converters, specifically wave generators. The integration of artificial intelligence emphasizes the potential of reliable models supporting the progress of oceanic renewable energy systems. The analysis presented in [82] explores synergy between renewable generators, lithium-ion batteries, and hydrogen-based power-to-power solutions in smart grids. Emphasizing the crucial role of hydrogen in achieving higher renewable fractions and its capacity for seasonal storage, the study suggests that hydrogen storage becomes fundamental beyond a 40% renewable penetration, maintaining system stability. Research by [83] focuses on the optimal operation of microgrids based on multi-agent systems, integrating diverse generation units with hydrogen and electric storage. Electric vehicles stand out as controllable loads and storage resources, emphasizing the importance of managing their charge and discharge. The inclusion of hydrogen-storage systems enhances energy management, leading to reduced operational costs and increased reliability.

The study in [84] delves into optimal energy management in parking lots, considering electric vehicles as controllable loads with vehicle-to-grid (V2G) capabilities. Despite the high battery-depreciation cost in V2G use, the study suggests that the inclusion of hydrogen-storage systems significantly increases profitability for parking-lot owners, simultaneously reducing energy demand during peak hours. In [85], a model for the optimal sizing of decentralized renewable energy communities (RECs) with hybrid storage, including hydrogen technology, is presented. The study employs a multi-objective genetic algorithm to observe the trade-off relationship between project cost and decarbonization. Results demonstrate that integrating hydrogen storage reduces costs, with a considerable decrease in greenhouse-gas emissions.

The evolution of hydrogen integration into electrical-distribution networks points towards various future trends reflecting the transformative role of this technology. Pioneering research by [79] emphasizes the need for attractive regulatory frameworks and business models to motivate prosumers to actively support the grid. The trend towards multi-carrier systems, as proposed in [82], suggests that combining different storage technologies, including hydrogen, will provide optimal flexibility and efficiency to handle the variability of renewable energy sources. Furthermore, Ref. [85] introduces the concept of renewable energy communities (RECs), representing a shift towards further decentralized and more sustainable systems. This approach could drive the widespread adoption of hydrogen-storage technology at a community level, maximizing economic and environmental benefits.

The innovative use of artificial intelligence in [81] to predict hydrogen production from wave generators highlights the growing importance of digitization and real-time prediction in efficient energy management. These advanced approaches could become key trends for optimizing performance and real-time decision making in renewable energy systems. Despite positive trends, the integration of hydrogen into electrical grids faces significant challenges. The study [80] notes that, despite reducing financial risk, initial investments and limited efficiency of hydrogen technology pose economic challenges. High implementation costs and limited efficiency are also highlighted in [84], emphasizing the need to overcome economic barriers for the widespread adoption of hydrogen-storage systems. The continued dependence on fossil fuels, as mentioned in [83], to obtain hydrogen through reforming processes presents a challenge in terms of sustainability and emissions reduction. Overcoming this dependence and moving towards green hydrogen production is essential to meet long-term environmental goals. The lack of clear standards and regulations for hydrogen integration into electrical grids, highlighted by [6], is a major obstacle that needs to be addressed to facilitate a seamless transition. Additionally, Ref. [85] emphasizes the need for further research to better understand economic and environmental aspects over time, highlighting the importance of assessing sustainability throughout the life cycle of systems.

The integration of hydrogen into electrical-distribution networks offers exciting opportunities but also faces considerable challenges. As we move towards a more sustainable future, the increasing decentralization of energy generation and the adoption of innovative technology like hydrogen will be fundamental. To overcome economic challenges and improve efficiency, investing in research and development is crucial. The implementation of advanced technology such as artificial intelligence for hydrogen-production prediction and multi-carrier-system optimization will be essential. Collaboration across sectors, governments, and industry will play a vital role in creating attractive regulatory frameworks and business models. Furthermore, increased investment in infrastructure and standards is needed to support the effective integration of hydrogen. In summary, the integration of hydrogen into electrical-distribution networks represents an exciting transition towards a more sustainable and resilient energy system. As we address current challenges, we are laying the groundwork for a cleaner and more efficient energy future.

### 4.3. Battery-Supercapacitor Hybrid Storage Systems

The integration of energy-storage systems and efficient energy management in electrical-distribution networks is critical to address current challenges associated with the transition to renewable energy sources and the electrification of various sectors. This evolutionary paradigm demands innovative solutions to enhance the efficiency and resilience of electrical grids. In the literature analysis, the proposal of a novel technology called a Hybrid Energy Storage System (HESS), combining batteries and supercapacitors, stands out. These systems, as evidenced in several studies [86,87], offer significant benefits in terms of voltage stability, power quality, and extension of battery lifespan, contributing to higher operational efficiency.

The work of [86] introduces a pioneering approach by proposing a HESS in a nanogrid structure, utilizing batteries in collaboration with supercapacitors to form a cloud energy-storage system. This innovative approach improves voltage stability and balances power in the common bus of nanogrids, showcasing smoother power variations and, consequently, extending battery life. The dual-level controller presented in [87] for managing a HESS in photovoltaic plants highlights the effectiveness of a synergistic exploitation of batteries and supercapacitors. This optimized approach addresses specific technical requirements for peak energy shaving and limiting the power ramp of the photovoltaic system, benefiting both the plant operator and the distribution-system operator.

The review in [88] focuses on distributed energy-storage systems (DES), including supercapacitors, to overcome challenges associated with the fluctuating nature of renewable generation. This work emphasizes the importance of precise optimization of multiple energy-device characteristics and uses artificial intelligence methods and PSO to achieve efficient performance. The stochastic optimization presented in [89] for the optimal scheduling of a microgrid with a HESS incorporating a battery and a supercapacitor underscores the importance of considering uncertainties associated with wind and solar generation and electric demand. This study provides valuable insights into the costs associated with adding supercapacitors in terms of stochastic performance.

The research in [90] delves into the optimization of HESS by analyzing key performance indicators (KPIs). It highlights the effectiveness of combining batteries and supercapacitors in terms of lifespan, energy density, and responsiveness, emphasizing the importance of intelligent control strategies for real-time operation and continuous optimization. Collectively, these studies offer a comprehensive insight into the benefits and challenges associated with the implementation of hybrid energy-storage systems in electrical-distribution networks. While emerging trends point toward advanced control strategies and the integration of diverse renewable energy sources, economic and regulatory challenges still pose significant hurdles that must be addressed for the widespread and sustainable adoption of these technologies in the future.

### 4.4. Superconducting Storage

The discussed citations focus on the application of superconductors in electrical-distribution networks, particularly in the context of fault current limiters and the electrical system of a fusion power plant. These applications demonstrate the potential of superconducting technology to address specific challenges in power systems. In the study [91], the challenges associated with the electrical system of the EU DEMO Plant are discussed. The paper highlights issues related to pulsed operation, high reactive-power demand, and the need for alternative technology to supply superconducting coils. The technical readiness level of identified alternatives is acknowledged as an area requiring further research and development. Studies [92,93] present practical implementations of resistive superconducting fault current limiters (SFCLs) in electric-power grids. These SFCLs demonstrate robustness and reliability in reducing fault currents, enhancing the stability of the grid. The successful operation of SFCLs in real-world scenarios provides valuable insights and references for future commercialization.

In [88], the study discusses the growing applicability of distributed generation units, particularly in microgrids, and the challenges associated with renewable energy fluctuations. The use of superconducting-magnetic-energy storage (SMES) and supercapacitor are proposed as alternatives to conventional batteries. The study emphasizes the role of advanced technology, artificial intelligence, and optimization techniques in enhancing the quality of electrical systems. The study [94] explores the integration of EVs into utility grids, focusing on the impacts of EVs on grid operation and the role of superconducting-magnetic-energy storage (SMES) in managing renewable energy fluctuations. The study introduces a fuzzy logic controller (FLC) system for coordinating EVs, SMES, wind energy, and the utility grid, resulting in improved grid performance. Future trends in the field of superconductors in electrical-distribution networks may include increased research and development to address challenges highlighted in the discussed studies, such as improving the technical-readiness level of alternative technology for supplying superconducting coils and enhancing the coordination of energy-storage devices in microgrids and utility grids. However, challenges remain, particularly in achieving higher technical-readiness levels (TRLs) for alternative technology, improving power-utilization factors, and addressing issues related to the pulsed operation of generators in fusion power plants. Additionally, future research may focus on optimizing architecture and control strategies for superconducting systems in various applications. In summary, the discussed studies underscore the potential benefits of superconductors in enhancing the efficiency, stability, and reliability of electrical-distribution networks. Ongoing research and development efforts are crucial to overcome existing challenges and unlock the full potential of superconducting technology in future power systems.

### *4.5. Microgrid Control Management*

The integration of microgrids into smart grids has garnered significant attention due to their potential to enhance energy quality and network stability. Microgrid technologies offer improved quality, stability, and sustainability of energy through advanced energy-control and -management systems [33]. The use of a model predictive control (MPC) has been proposed for energy scheduling in smart microgrids with RESs and energy-storage systems to optimize the operation of controllable electrical appliances and enhance the overall performance of the microgrid [95]. Additionally, the implementation of an intelligent microgrid based on a multi-agent system has been suggested to dynamically and autonomously adjust voltage and industrial frequency reactive power drop curves, thus enhancing energy quality and reliability. Furthermore, the concepts of smart grids and microgrids are interconnected, emphasizing the need for intelligent control architecture to manage bidirectional energy flow between the smart grid and the microgrid, ensuring efficient energy-flow management and peak reduction [10].

Coordinated control of battery energy-storage systems and dispatchable distributed generation using fuzzy logic has been proposed to minimize active energy exchange and improve frequency control in microgrids. The use of microgrid technology on islands has transcended laboratory settings. Niusan Island, located over 60 km from Lianyungang, has transformed into a microgrid with 30 kW of rooftop PV power generation, a 30 kW diesel generator, and lead–carbon battery energy storage to meet the electricity demand of communication equipment, a seawater desalination system, air conditioning, refrigeration, and daily lighting. PV, diesel-power generation, and integrated wind energy storage in distributed energy-generation battery systems have been adopted on another island known as Nanlu Island [78].

Microgrids, characterized as complete power systems with innovative technology, are positioned as essential elements in the future smart grid architecture [96]. The evolving landscape of microgrid research has produced a series of insightful studies addressing various aspects of control and management strategies to unlock their economic, social, and environmental benefits. In the study [97], a comprehensive exploration of microgrid control is presented, with a focus on grid connection and seamless transition modes. This research highlights the need for robust control strategies for AC microgrids, stressing the importance of synchronization, seamless transfers, and power management. The discussion extends to acknowledge the existing gaps, particularly in addressing DC microgrids and power electronics structures. Energy-management systems for microgrids take center stage in the study conducted by [98], where the challenges associated with the rising electrical-power demand are addressed. This research reviews various strategies for load-demand, energy-generation, and energy-storage-system management, pointing towards a future dominated by metaheuristic optimization approaches, including artificial intelligence. The paper anticipates the evolving landscape of microgrid energy management, emphasizing the efficiency brought about using advanced optimization techniques.

The exploration of the concept of multi-microgrids (MMGs) and their potential economic benefits are presented in [99]. This study emphasizes the importance of cybersecurity in MMGs and envisions future advancements in coordination schemes and robust MMG architecture, acknowledging the challenges posed by factors such as electrical-load variation and cyberattacks. The comprehensive review offers insights into contemporary MMG architecture and energy-management functionalities. The adoption of digital-twin technology in microgrids to enhance operational efficiency is introduced [99]. The paper reviews applications of digital twins in microgrids, emphasizing their role in real-time monitoring, predictive analytics, and optimization. Future research trends are suggested to focus on addressing challenges related to the implementation of digital twins, including data collection, scalability, and interoperability. Hierarchical control and estimation schemes are explored in [100], categorizing control technologies into six types for smart microgrids. This research advocates for a future vision involving advanced estimation techniques and the development of hierarchical and architectural control techniques. The need for excellent monitoring behavior to protect microgrids against unexpected events is emphasized, providing a foundation for future research.

In the comprehensive review by [101], energy-management strategies in microgrids from 2009 to 2022 are systematically classified based on their technique, control strategies, and structure. This study offers insights into the development of energy-management systems, highlighting ongoing research, latest developments, and potential future directions. The paper stresses the importance of industry and academic focus on making the energy sector more efficient and sustainable. These collective insights into microgrid control and management strategies, derived from a series of well-researched studies, provide a comprehensive overview of the current state of the field. The identified future trends involve the integration of advanced technologies, addressing emerging challenges, and exploring innovative solutions, ultimately contributing to the efficiency, manageability, and sustainability of microgrid ecosystems.

## 5. Carbon-Emission Reduction and Challenges

### *5.1. Carbon-Emission Reduction*

The revolution in electric-distribution networks, marked by the transition to renewable sources, has triggered significant changes in global-carbon-emission reduction. As of 2022, more than 26% of the globally generated electricity comes from RESs, according to the International Energy Agency (IEA) [102], indicating a clear trend towards a more sustainable approach. This shift has not simply been symbolic, as between 2010 and 2021, the adoption of renewable energy in electric networks contributed to reducing over 2.3 billion tons of $CO_2$ emissions, as per data from the United Nations Environment Programme (UNEP) [103]. This significant impact underscores the crucial role played by renewable energy in mitigating climate change.

The exponential growth in installed solar and wind energy capacity, which surged by over 300% over the last decade, according to the International Renewable Energy Agency (IRENA) [104], is further evidence of the expansion of this clean technology. This increase not only reflects technological advancements but also substantial global investment, reaching a record of over 300 billion dollars in renewable energy projects in 2021, according to BloombergNEF [105].

However, challenges persist. Despite remarkable achievements, carbon emissions associated with electric generation still represent a significant portion of their total. The intermittency of renewable sources underscores the need for advanced storage solutions to ensure a constant energy supply. In this context, the global reduction of carbon emissions in electric-distribution networks based on renewable energy stands as a tangible achievement but also serves as a reminder of the ongoing need to address challenges and strengthen efforts towards a more sustainable future. International collaboration and the implementation of effective policies are essential to solidify these advancements and progress towards a truly sustainable global energy landscape.

### *5.2. Challenges*

Currently, the smart grid operates as a passive network, and the challenge lies in generating a greater flow of data focused on auxiliary services connected to the system while maintaining robustness in the network [106]. Smart grids, heavily reliant on information networks, are vulnerable to potential threats [21]. Therefore, ensuring fast, reliable, and secure communication in smart grid environments is essential for better data governance, enabling the distributor to formulate improved energy-distribution strategies in the smart grid.

In Figure 9, two blocks are visualized. The first block deals with operational data and energy distribution depending on prosumer requirements. The second block represents transactional data and how AI aids improvement through the required information. This facilitates intelligent distribution, efficiently supplying the necessary energy to each operational data point. Information technologies remain in constant connection with both operational and transactional data, enabling control over economic aspects, data management, and cybersecurity. This creates an active intelligent distribution that benefits all network stakeholders. It is crucial to understand that the information in the first block is related to the energy needed in each process, in addition to the database for real-time prosumer operations. Reaching a balance that allows for achieving the efficiency of the existing network infrastructure and delivering greater benefits to the end customer is crucial. As the system becomes increasingly digitized, there will be an increasing amount of available information for managing resources in real-time and refining auxiliary systems. Efficient operability with new business models, such as peer-to-peer electricity trading, coupled with regulatory standards that can prevent economic losses in the maintenance of power lines, is essential.

Despite notable advancements in transitioning to renewable-energy-based electrical grids, substantial challenges are emerging that necessitate ongoing research and development to ensure long-term sustainability and efficiency.

#### 5.2.1. Integration of Intermittent Renewable Energy

The integration of intermittent sources, such as PV and wind energy, confronts the formidable challenge of variability in generation. Research efforts are strategically directed towards the development of advanced storage technology. This includes the exploration of cutting-edge solutions like flow batteries and thermal-storage systems. This sector has experienced a substantial 30% surge in global-energy-storage investments, reaching a noteworthy $4.2 billion in 2021, as reported by [105]. This underscores the critical importance of innovative storage mechanisms to enhance the reliability of intermittent renewable energy sources.

#### 5.2.2. Optimization of Smart Grids

Optimizing smart grids necessitates the application of sophisticated algorithms to manage their intricate functionalities. The research landscape in this domain is buoyed by the unprecedented growth of AI in the electrical sector. A staggering projected global investment of $13.2 billion by 2025, as indicated by Statista, propels the exploration of advanced algorithms to optimize the performance of smart grids. This showcases the pivotal role that AI plays in augmenting the efficiency and adaptability of intelligent electrical grids [106].

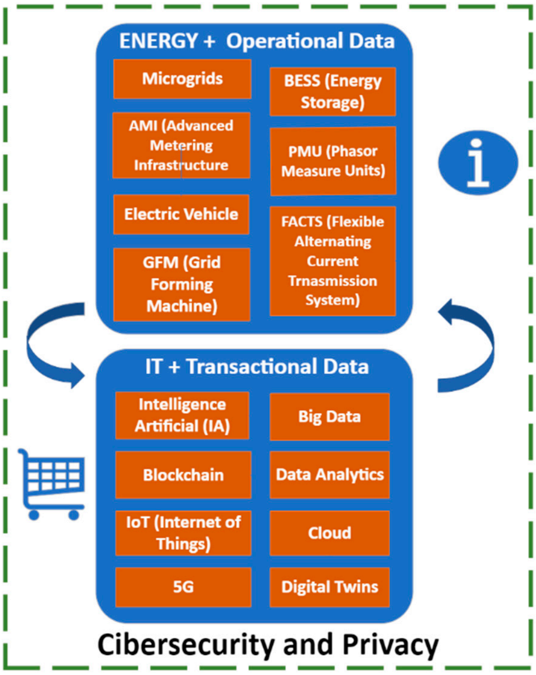


**Figure 9.** More robust data network with proper real-time information management.

5.2.3. Electrification of Non-Electric Sectors

The ambitious goal of electrifying non-electric sectors brings forth the demand for innovative technology. Research in electrolysis for hydrogen production has intensified as a viable solution. This area has witnessed a substantial 40% increase in investments in green hydrogen projects during 2021, according to data from the Hydrogen Council. This underscores the increasing recognition of hydrogen as a pivotal element in achieving a sustainable and electrified future for various industrial sectors [107].

5.2.4. Development of Charging Infrastructure

With the proliferation of EVs, the development of robust charging infrastructure assumes paramount importance. Research is underpinned by a substantial 60% surge in global investments in charging stations, reaching a notable $3.8 billion in 2022, as reported by the IEA. This highlights the critical need to establish a comprehensive charging network to support the widespread adoption of EVs, fostering a seamless and sustainable transportation ecosystem [108].

5.2.5. Adaptation of Policies and Regulations

The transition to renewable energy demands a recalibration of policies and regulations to facilitate a supportive environment. Research efforts focus on evolving regulatory frameworks, with a 25% increase in government initiatives observed over the last three years, according to REN21. This emphasizes the dynamic nature of policy-making, crucial for fostering an environment conducive to the widespread adoption of renewable energy solutions [109].

5.2.6. Resilience to Climate Threats

Ensuring resilience to climate threats requires strategic investments in robust technology. Research highlights a substantial 35% increase in investments in climate-resilient infrastructure in 2021, totaling an impressive $7.6 billion, as reported by the Global Infrastructure Hub. This emphasizes the imperative of fortifying infrastructure against the adverse impacts of climate change, ensuring a resilient and adaptive electrical grid [110].

#### 5.2.7. Community Engagement and Education

Recognizing the pivotal role of community engagement, research reveals a commendable 20% increase in the adoption of sustainable energy practices in participatory communities, according to reports from government agencies. This underscores the significance of fostering community involvement and awareness to drive sustainable energy practices at the grassroots level.

These figures collectively underscore the magnitude of investments and momentum behind the mentioned research areas. As they face significant challenges, these research efforts are not only crucial for overcoming technical obstacles but also represent key opportunities for sustainable growth and global-scale climate-change mitigation. The intersection of innovative technologies, strategic policies, and community engagement holds the key to addressing the complexities of the evolving energy landscape.

## 6. Discussions and Future Perspectives

The rapid evolution of smart electrical networks and the integration of RESs have ushered in a transformative era in the field of electrical distribution. As we delve into the multifaceted aspects of this paradigm shift, several noteworthy discussions emerge, paving the way for future perspectives and research directions.

### *6.1. Technological Advancements and Network Architecture*

The intricate architecture of smart electrical networks, as explored in Section 2, signifies a pivotal point in technological progress. The discussion revolves around the seamless integration of renewable sources, emphasizing the need for adaptive infrastructure that accommodates distributed energy resources. The adoption of advanced communication technology, such as bidirectional internet and IoT, has laid the foundation for bidirectional energy flows, enabling efficient energy trading among prosumers.

Furthermore, the analysis of recent studies highlights various perspectives on technological advancements and the architecture of smart electrical grids, underscoring the importance of adapting to the growing presence of renewable sources and the need for flexible infrastructures. Study [111] proposes an optimal allocation method for partitions in power-distribution networks, utilizing an enhanced spectral clustering algorithm. This proposal emphasizes the need for advanced partitioning strategies to optimize system performance. The discussion focuses on how these strategies can enhance network efficiency, emphasizing the importance of adapting the architecture to accommodate changes in energy generation and demand. Regarding the robustness assessment of renewable-energy-integrated electrical networks [112], there is an emphasis on addressing challenges associated with renewable source integration to ensure system stability. This approach involves considering the inherent variability of these sources and applying specific strategies to maintain network robustness. The discussion centers on how the architecture of electrical networks must evolve to accommodate these complexities and ensure a smooth transition to increased renewable energy participation.

Study [113] addresses the reconfiguration of distribution networks in the presence of distributed generation and demand uncertainty. The importance of considering variability and fluctuations in load for achieving a robust reconfiguration is highlighted. The discussion implies the need to adapt the architecture of electrical networks to respond efficiently to dynamic changes in energy generation and demand. The strategy presented in study [114] aims to enhance resilience in electrical networks with multiple energy sources, emphasizing the effectiveness of subdividing subnetworks and distributing energy to strengthen system defense. The discussion focuses on how these approaches can be integrated into the architecture of electrical networks to ensure a robust response to adverse events. Finally, study [115] proposes a methodology for measuring robustness in reverse logistic supply chains. The application of methods based on information theory and nodal importance proves to be efficient. The discussion centers on how these methods can be adapted and applied in the architecture of electrical networks to improve resilience and operational efficiency. Collectively, these studies underscore the need to evolve the architecture of electrical networks to address specific challenges related to distributed generation, the integration of renewable sources, and resilience against adverse events. Adapting the infrastructure is essential to ensure an efficient, sustainable, and robust electrical system in the future.

### *6.2. Sustainable Technological Innovations*

Section 3 highlights the remarkable strides in sustainable technology within electrical-distribution networks. The discourse encompasses the role of energy-storage units, self-charging storage devices, and the potential of IoT-enabled smart grids. Notably, the discussion extends to the promising applications of blockchain technology, accentuating its significance in enhancing security, resilience, and trust in smart grids.

The examination of the selected studies sheds light on diverse perspectives concerning sustainable technological innovations and their impact on network architecture within the electrical system's domain. The overarching theme emphasizes the necessity of aligning technological advancements with sustainability goals, particularly in the context of smart grids and distribution networks. The study conducted by [116] delves into the realm of advanced measurement and automation infrastructures, along with computational-intelligence mechanisms. This research introduces opportunities to enhance the operational efficiency of electrical systems and power quality indicators within the framework of smart grids. The deployment of an architecture for advanced distribution automation (ADA) applications, including tools such as state estimators, voltage control, and fault-location mechanisms, showcases a commitment to sustainability through improved grid management.

In a parallel context, Industry 4.0 emerges as a transformative force, influencing various sectors, including energy. Addressing challenges posed by aging equipment and evolving demand, the study by [117] explores how Industry 4.0 tools can revolutionize asset management for electrical networks. The integration of big data, smart grids, and data analytics plays a pivotal role in optimizing resource allocation, enhancing failure prediction, and supporting sustainability goals within the electricity production, transmission, and distribution chain. Advancements in smart grid technology and renewable energy are integral components of a sustainable electricity system. However, the integration of these technologies necessitates effective data management and utilization, as highlighted by [118]. The study underlines the potential of big data in monitoring, correcting, and integrating smart grid technologies and renewable energy sources. Successful integration requires addressing technological, economic, institutional, and policy constraints, emphasizing the intricate balance required for sustainability in electric utilities. The role of active distribution networks (ADNs) is in leveraging smart building prosumers, plug-in electric vehicles (PEVs), and aligns with sustainable-development objectives. Ref. [119] introduces an optimization method for the sustainable operation of ADNs, emphasizing the importance of smart power dispatch techniques and hierarchical multi-agent systems. The demonstrated reduction in operation costs signifies a step towards sustainable energy practices. Moreover, the study [120] tackles the challenges encountered by parallel hybrid electric vehicles (PHEVs) during mode transitions, specifically focusing on drivability issues arising from clutch-torque-induced disturbances. The proposed coordinated control strategy integrates motor and engine controls, employing a sliding mode-control strategy based on a group-preserving scheme for motor control. Additionally, an adaptive PI controller is implemented for engine speed regulation, addressing torque interruptions and model uncertainties. Through hardware-in-the-loop simulations, this strategy demonstrates a substantial reduction in vehicle jerk, effective mitigation of frictional losses, and an overall enhancement in driving comfort and reliability. Shifting the focus to energy management in hybrid energy systems, the study [121] introduces a knowledge-based, multiphysics-constrained energy-management strategy tailored for hybrid electric buses (HEBs). This strategy prioritizes thermal safety and prevents degradation in the lithium-ion-battery (LIB) system. By incorporating the overtemperature penalty and multistress-driven degradation cost of LIB into the optimization target and utilizing a soft actor-critic deep reinforcement learning (SAC-DRL) strategy, the proposed approach outperforms existing methods. It achieves a significant reduction in training time, effectively controls internal battery temperature, enhances fuel economy, and reduces overall driving cost under different road missions.

Lastly, distribution-network-expansion planning (DNEP) emerges as a critical aspect of sustainable energy infrastructure. Ref. [122] offers a comprehensive overview, considering evolving challenges introduced by renewable energy sources and changes in market dynamics. The paper suggests that addressing these challenges through advanced methodologies and a focus on environmental considerations is crucial for the sustainable evolution of distribution networks. In conclusion, these studies collectively underscore the need for sustainable technological innovations in network architecture. Whether through advanced automation, Industry 4.0 tools, effective data management, optimized operation of distribution networks, or strategic expansion planning, the integration of sustainability principles is imperative for the future resilience and efficiency of electrical systems.

### 6.3. Energy Efficiency and Quality Distribution

The critical intersection of energy efficiency and quality distribution, elucidated in Section 4, opens avenues for robust deliberations. The focus lies on innovations, such as FLISR, which play a pivotal role in achieving self-healing capabilities within smart grids. The integration of artificial intelligence in the form of VPPs is explored, showcasing their intermediary role in balancing distributed energy resources, controllable loads, and EVs.

The optimization of energy systems within aircraft power structures is crucial for addressing the rising demand for electrical energy and achieving sustainable, efficient operations. This discussion encompasses several studies focusing on energy efficiency and quality distribution within the context of aircraft power systems, shedding light on innovative methodologies and technological advancements. In the study [123], the emphasis is on minimizing losses in transmission and distribution grids, recognizing the impact of these losses on system efficiency and cost. The study introduces an economic and swift methodology utilizing artificial neural networks (ANN) to estimate losses in distribution grids. This approach aligns with the overarching goal of enhancing energy efficiency by forecasting and comparing actual energy losses, thereby providing valuable insights for sustainable distribution networks. Moving to the study [124], a multi-objective optimization approach is presented for the allocation of RESs and the implementation of distribution-static synchronous compensators (D-STATCOM) and passive power filters (PPFs) in electrical-distribution networks. The study employs advanced metaheuristic algorithms, specifically artificial rabbit optimization (ARO), to significantly reduce power losses and improve power quality. This integration of RESs and compensation technologies exemplifies a holistic strategy for achieving energy efficiency and maintaining high-quality distribution in electrical networks.

The study [125] explores the transformation of electrical power grids in the aviation sector, with a specific focus on hybrid AC/DC grids, solid-state transformers (SST), and unified power electronics systems. These advancements are presented as contributors to improved flexibility, efficiency, and power quality. The study underscores the importance of embracing innovative technology to enhance energy efficiency and ensure quality distribution within future power grids for aircraft.

Shifting to the regulatory context, the fourth study [126] delves into the quality of electricity supply, particularly in South American countries. By conducting a comprehensive literature review, the study evaluates regulatory aspects, metrics, and compensation structures associated with maintaining a high-quality electricity supply. This perspective provides valuable insights into the regulatory frameworks needed to ensure efficient and reliable energy distribution. Then, the study [127] navigates the complexities of energy optimization and management in More/All-Electric Aircraft (MEA/AEA) and Electrical Propulsion Aircraft (EPA). The review encompasses architecture optimization, energy-management systems (EMS), and predictive health management (PHM). By examining the integration of AI in EMS and the interaction between microgrids and electric-propulsion aircraft, the study positions itself at the forefront of addressing challenges and opportunities in achieving energy efficiency and quality distribution.

### *6.4. Carbon-Emission-Reduction Challenges and Strategies*

The reduction of carbon emissions, as discussed in Section 5, underscores the commendable progress achieved through the integration of renewable energy sources. However, the discussion expands to acknowledge the challenges posed by the intermittent nature of renewable resources. Advanced storage technology, optimization algorithms for smart grids, and the electrification of non-electric sectors emerge as critical strategies to address these challenges.

Addressing the global challenge of sustainable energy consumption and production, the first paper proposes a multi-objective function model for a smart micro-grid (SMG) [128]. The model aims to minimize operation cost, emission pollution, and the deviation between the original and desired demand curves. Particularly noteworthy is the introduction of a strategy involving responsible customers (RCs) with shiftable loads to manage demand consumption. By optimizing these objectives, the study demonstrates a significant reduction in operation costs and emissions, showcasing the potential of this model in contributing to carbon-emission-reduction challenges [128]. The emphasis on minimizing emission pollution aligns with the broader goal of creating environmentally friendly energy systems. The transition from fossil fuel to renewable-based electricity generation, discussed in [129], introduces a P2P energy-trading framework using advanced-electric-storage water heaters. This framework maximizes renewable generation for individual consumers and addresses local grid problems. The study highlights benefits such as increased PV self-consumption and financial savings. The results from this research emphasize the potential of P2P energy trading to contribute to carbon-emission-reduction challenges by promoting decentralized renewable energy systems and optimizing energy usage.

The concerns associated with the increasing number of data centers and their impact on electricity demand and the environment are addressed in [130]. The proposed CCHP-PV systems in a data center, coupled with residential customers, demonstrate the potential to eliminate the data center's electricity demand from the grid, reduce residential energy demand, and decrease carbon emissions. By contributing to sustainable energy goals, this research provides insights into strategies that can effectively reduce carbon emissions in the context of growing data-center operations. The study [131] focuses on air quality and energy consumption in seaports, specifically in fishery activities, and proposes a simulation-based strategy to optimize energy usage. By integrating renewable energy sources and smart grid technologies, the study suggests the formation of energy communities at the port level, contributing to carbon-emission reduction. The co-simulation environment and optimized energy strategies presented in this research offer insights into efficient methods for managing energy consumption in fish-processing industries, ultimately reducing their carbon footprint.

### *6.5. Future Research Directions*

Looking ahead, the trajectory of research in smart electrical networks points towards several compelling directions. The integration of artificial intelligence in optimizing smart grids demands further exploration, with a focus on refining algorithms for enhanced grid efficiency. Investigating the scalability and reliability of emerging technology, such as blockchain, remains a key avenue. Moreover, the role of electrification in non-electric sectors, particularly through hydrogen production, demands in-depth research to drive sustainable solutions. The development of charging infrastructure for EVs necessitates comprehensive studies on scalability, interoperability, and energy storage.

The evolving landscape of policies and regulations requires continuous research efforts to align with the dynamic nature of smart grids. Additionally, community-engagement strategies need refinement for broader adoption of sustainable energy practices. In summary, the discussions and future perspectives outlined in this section encapsulate the dynamic and evolving nature of smart electrical networks. They set the stage for continued research, technological innovation, and collaborative efforts to build a resilient, sustainable, and efficient energy ecosystem for the future.

Likewise, the trajectory of research in smart electrical networks points towards several compelling directions, as highlighted by recent studies. The integration of artificial intelligence in optimizing smart grids, as discussed in the first citation, demands further exploration within the broader context of smart electrical networks. Future research could delve into refining machine-learning algorithms to enhance grid efficiency, addressing challenges such as the scalability, reliability, and the interoperability of intelligent systems. The potential synergies between AI and other emerging technology, like blockchain, should be thoroughly investigated to create integrated solutions that maximize the benefits of each component [132]. Furthermore, the development of charging infrastructure for EVs emerges as a critical research area, as outlined in the second citation. Scalability, interoperability, and efficient energy storage for EV charging systems require comprehensive studies. Future research directions could explore innovative solutions to optimize charging infrastructure, ensuring seamless integration with the evolving smart electrical networks. Additionally, the role of EVs in grid stability and their interaction with renewable energy sources present intriguing topics for exploration [100].

The discussions around the marine predators algorithm (MPA) in the third citation open avenues for nature-inspired optimization algorithms in smart electrical networks. Future research efforts could focus on enhancing the robustness, efficiency, and versatility of MPA. Exploring mixed-integer variants, constrained variants, and parameter-less variants of MPA may offer novel optimization strategies. Furthermore, investigating the potential application of MPA in specific domains, such as image processing, classification, and electrical-power systems, can contribute to the broader landscape of smart electrical networks [133]. Moreover, the envisioned research directions align with the broader perspectives outlined in the overarching discussion on smart electrical networks. Investigating the scalability and reliability of emerging technology, including blockchain, remains a key area of interest. The role of electrification in non-electric sectors, particularly through hydrogen production, demands in-depth research to drive sustainable solutions and establish new paradigms for energy consumption. Continuous efforts in policy and regulation research are crucial to navigating the dynamic landscape of smart grids. Additionally, refining community engagement strategies is essential for the broader adoption of sustainable energy practices. In summary, the multifaceted discussions and future perspectives outlined in this section encapsulate the dynamic and evolving nature of smart electrical networks. They set the stage for continued research, technological innovation, and collaborative efforts to build a resilient, sustainable, and efficient energy ecosystem for the future.

## 7. Conclusions

The current trajectory of the electrical grid's evolution reflects a multifaceted transition, embracing both technological advancements and a cultural shift. Striking a delicate balance between user-centric needs and the imperatives of an intelligent distribution network is paramount. The overarching goal is to provide efficient services to prosumers, minimize grid congestion, and uphold cost-effectiveness while adhering to market principles, ensuring a collective benefit for all stakeholders.

Our comprehensive review has unveiled noteworthy technological strides, exemplifying practical cases in energy-quality systems. The integration of renewable energy sources, deployment of energy-storage systems, digitalization of electrical infrastructure, and implementation of smart devices and meters collectively promise not only a more agile and efficient network operation but also a refined approach to energy-quality management. The integration of blockchain technology into smart grids marks a transformative juncture in the energy sector. Beyond addressing challenges and security concerns, the potential benefits of a secure, decentralized, and transparent framework for energy transactions paves the way for a future energy system characterized by heightened efficiency, resilience, and security.

Looking ahead, smart grids confront substantial challenges that demand continued research and development efforts. As we navigate an era of increased digitalization, seamless integration of technologies like 5G, robust cybersecurity measures, the expansion of distributed generation, and the persistent electrification of the economy become imperatives. It is evident that the electrical grid is rapidly advancing toward a more sophisticated and digitized form, shaping a pivotal trajectory towards a sustainable energy future. The collaboration of international efforts and the implementation of effective policies will be indispensable to consolidate these advancements and propel us towards a truly sustainable global energy landscape.

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