algorithms

MDPI

Review

Emerging 6G/B6G Wireless Communication for the Power Infrastructure in Smart Cities: Innovations, Challenges, and Future Perspectives

Ahmed Al Amin , Junho Hong , Van-Hai Bui and Wencong Su *

Department of Electrical and Computer Engineering, University of Michigan-Dearborn, Dearborn, MI 48128, USA; ahalamin@umich.edu (A.A.A.); jhwr@umich.edu (J.H.); vhbui@umich.edu (V.-H.B.)
* Correspondence: wencong@umich.edu

Abstract: A well-functioning smart grid is an essential part of an efficient and uninterrupted power supply for the key enablers of smart cities. To effectively manage the operations of a smart grid, there is an essential requirement for a seamless wireless communication system that provides high data rates, reliability, flexibility, massive connectivity, low latency, security, and adaptability to changing needs. A contemporary review of the utilization of emerging 6G wireless communication for the major applications of smart grids, especially in terms of massive connectivity and monitoring, secured communication for operation and resource management, and time-critical operations, are presented in this paper. This article starts with the key enablers of the smart city, along with the necessity of the smart grid for the key enablers of it. The fundamentals of the smart city, smart grid, and 6G wireless communication are also introduced in this paper. Moreover, the motivations to integrate 6G wireless communication with the smart grid system are expressed in this article as well. The relevant literature overview, along with the novelty of this paper, is depicted to bridge the gap of the current research works. We describe the novel technologies of 6G wireless communication to effectively perform the considered smart grid applications. Novel technologies of 6G wireless communication have significantly improved the key performance indicators compared to the prior generation of the wireless communication system. A significant part of this article is the contemporary survey of the considered major applications of a smart grid that is served by 6G. In addition, the anticipated challenges and interesting future research pathways are also discussed explicitly in this article. This article serves as a valuable resource for understanding the potential of 6G wireless communication in advancing smart grid applications and addressing emerging challenges.

Keywords: 6G; applications of smart grid; key performance indicators; smart city; smart grid; wireless communication

check for updates

Citation: Al Amin, A.; Hong, J.; Bui, V.-H.; Su, W. Emerging 6G/B6G Wireless Communication for the Power Infrastructure in Smart Cities: Innovations, Challenges, and Future Perspectives. *Algorithms* **2023**, *16*, 474. https://doi.org/10.3390/a16100474

Academic Editor: Arun Kumar Sangaiah

Received: 6 September 2023
Revised: 4 October 2023
Accepted: 7 October 2023
Published: 9 October 2023

1. Introduction

The smart city consists of a number of key enablers, which are smart education, smart healthcare, a smart economy, smart factories, smart warehouses, smart transportation, etc. [1,2]. The key enablers of smart cities require uninterrupted and efficient power supplies to fulfill their requirements [1–3]. Moreover, to effectively pursue all the functionalities of a smart grid system, a suitable wireless communication is required that can provide a high data rate, reliability, flexibility, low latency, massive connectivity, security, and the necessary adaptive functionalities [1,4]. Among the various applications of the smart grid, massive connectivity and monitoring, secured communication for resource allocations and operations, and time-critical operations are the vital factors in the case of an effective, uninterrupted, and reliable power supply for smart cities [5,6]. Future 6G wireless communication is a suitable solution for the communication of smart grid systems by providing all the required key performance indicators (KPIs) in terms of communication to successfully perform the abovementioned smart grid applications [7–9].

The smart city consists of several key enablers, which are the smart grid, smart factories, smart warehouses, smart healthcare, smart transportation, smart education, a smart economy, smart agriculture, a smart environment, etc., and these are illustrated in Figure 1. The aim of providing a smart, uninterrupted power supply and management is the prime concern for successfully operating all of the smart city applications [1,10–12].

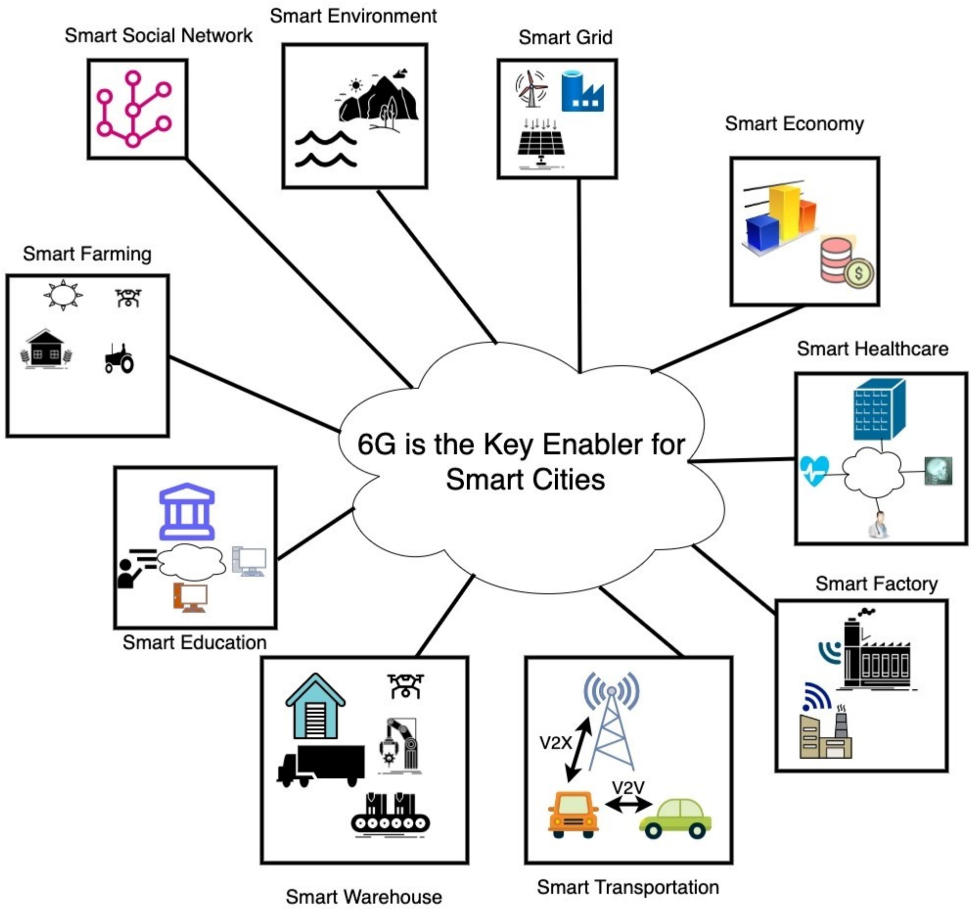

Figure 1. Key Enablers of the Smart City.

Each of the smart city key enablers require their own respective power requirements [13–18]. Thus, an uninterrupted smart power supply is the basic requirement for the key enablers to conduct all of the smart applications of smart cities. The smart grid is a viable power supply and distribution remedy for the smart city key enablers. Moreover, the advancement of the smart grid is a trendy research area. The basics of the smart city and the smart city key enablers are briefly introduced in Section 1.1. Moreover, the overview of the smart grid and 6G wireless communication are briefly introduced in Sections 1.2 and 1.3. The relevant literature overview of the previous works and the motivation of this paper are described in Section 1.4. In addition, the key contributions of this article are briefly described in Section 1.5.

1.1. Basics of the Smart City

The term "smart city" signifies a developed urban locality that ensures sustainable development with regard to the economy, as well as enhanced living standards by prevailing various key features such as industry, economy, education, health care, transportation, government, people, and living standards [19]. The smart city is a unique way through which to solve urban problems [20].

Smart applications are integrated into smart cities—whose daily activities are related to the modern technologies in the world [21]. Cities should have interconnected technology and management, along with peaceful and interactive living standards [20,21]. Therefore, the smart city can promptly overcome the worst scenarios and destructive crises [22]. According to Figure 1, the smart city is based on ten major key enablers. Furthermore, all the key enablers are equally important for the feasible advancement of smart cities [1,23]. The major smart city key enablers are briefly described as follows:

1.1.1. The Smart Grid

The smart grid is a future electrical network encompassing four major domains: bulk generation, transmission, distribution, and consumer segments. Moreover, uninterrupted communication between the domains is essential for the smart grid system [24]. Furthermore, the Internet of Things (IoT) and artificial intelligence (AI) are also integrated with the power grid in the case of the smart grid system [24]. In addition, the smart grid is not only a sustainable, cost and power-effective power supply solution, but it also provides high-quality, low losses, as well as a safe and secure power supply [25–27].

1.1.2. Smart Education

Distance learning is a common method of teaching in the current education system [28,29]. Moreover, future distance learning, or education systems, require a higher quality of Internet service, along with real-time interactions and lower power consumption [29]. Moreover, the improvement of the quality of remote learning and education will enhance the number of quality human resources, improve employment productivity, support influential institutions, and secure sustainable economic advancement [13].

1.1.3. Smart Transportation

Smart transportation is another key enabler for a sustainable smart city [30]. Smart transportation requires different communication technologies, such as vehicle-to-everything (V2X), vehicle-to-grid (V2G), vehicle-to-infrastructure (V2I), vehicle-to-vehicle (V2V), vehicle-to-pedestrian (V2P), vehicle-to-cloud (V2C), vehicle-to-device (V2D), etc. Smart transportation avoids collisions, saves energy, and improves road-safety, as well as increases the efficiency of traffic [31]. Thus, smart transportation can play a crucial role in the economic advancement of the smart city.

1.1.4. Smart Healthcare

Smart healthcare is a crucial key enabler for smart cities [32,33]. Smart healthcare can provide intra-hospital observation, remote patient monitoring, virtual healthcare, long-distance surgery, remote learning for doctors and nurses, remote diagnoses, emergency services, and remote consultations [17]. These applications required new technologies like virtual reality (VR) and augmented reality (AR) which require real-time, reliable, low latency, and flexible communication networks [1,17]. Smart healthcare ensures precise and high-quality medical care for the residents of smart cities.

1.1.5. Smart Farming

Smart farming introduces information and communication technology (ICT) in the agricultural and farming sectors of smart cities [34]. The IoT, sensors, actuators, unmanned aerial vehicles (UAV), robots, geopositioning, big data, and other ICT applications are to be introduced into the cultivation process of the agricultural sector [34]. Several evolving technologies are to be introduced into smart farming like smart machines, crop sensors, cloud computing, as well as the IoT for the smart control, analysis, and planning of farming [35]. The process of smart farming consists of smart analysis and planning, smart sensing and monitoring, smart control, and storing big data in cloud devices [36]. Smart farming not only reduces labor requirements, but it also enhances the caliber of production [37].

1.1.6. Smart Social Networking

The popularity of social platforms and people from different categories are connected through online social networking (OSN) [38]. The data from OSN provide social, cultural, and economic information, which are utilized by the commercial industries, authorities, policymakers, and governments of smart cities to realize the market trends and behavioral patterns of smart city residents [39]. Therefore, the effective progression of smart cities is linked to individual behavior within online social networking (OSN) platforms [40,41].

1.1.7. Smart Factory and Smart Warehouse

The smart factory is defined as an intelligent or digital factory [42]. A fully connected manufacturing system is introduced in the case of the smart factory, which can operate without any human force by data generation, transmission, reception, and processing for production purposes [43]. Smart factories introduce novel technologies in the case of production, such as a cyber physical system (CPS), AI-based decision making, intelligent data exchange models, human–machine interactions, cloud-enabled manufacturing and services, and comprehensive connections for the IoT for the effective production of goods and the minimization of human forces [42,43].

The smart warehouse provides high-quality services for the residents of smart cities [44]. Moreover, the smart warehouse enhances the productivity of supply chain management and also provides advantages to the stack holders of the communities within smart cities [45].

1.1.8. Smart Environment

The smart environment is a vital key enabler for the advancement of the smart city [46]. The smart environment changes the city and also reshapes the environment of the city for the settlement of the residents [47]. Moreover, various environmental challenges such as waste management and the pollution of the smart city can be effectively handled by the smart environment [48,49]. Furthermore, AI-based intelligent resource management in the smart environment is also a vital factor for smart cities.

All of the functionalities of the abovementioned key enablers of the smart city, as well as smart power supply and management, are required to be uninterrupted. As mentioned earlier, the smart grid is a viable solution for fulfilling the power supply requirements of the smart city key enablers. Therefore, the basic principles of the smart grid system are described in Section 1.2.

1.2. Basic Principles of the Smart Grid

The basic electrical power system is a network that consists of the generation, transmission, and distribution of electrical power [2,50,51]. The electrical power system that supplies electrical power to the user (e.g., in industry and the home) in a large geographical area is termed an electric grid [51]. The basic smart grid system consists of four major domains, which were mentioned earlier in Section 1.1.1. Figure 2 illustrates the basic structure of the smart grid framework [3,6,52,53]. The smart meter is integrated with the smart grid, which can provide intelligent functionalities such as bidirectional energy trading, decentralized power generation, energy redistribution, request coordination, etc., for the smart and uninterrupted power supply of each key enabler of the smart city [54]. Compared to the conventional power grid, the communication network is integrated with the smart grid architecture to provide different functionalities, such as effective energy redistribution and utilization, as well as price negotiation [15]. The smart grid communication network consists of four distinct kinds of networks (e.g., the Internet, the wide area network (WAN), the substation local area network (LAN), and the premises area network) [55]. By utilizing the various networks, all the major domains of the smart grid are interconnected and would also communicate with the market, operator office, and service provider to perform the functionalities of the smart grid [2,3,6,50–53]. Moreover, AI, the IoT, and CPS would also be integrated with smart grids to elevate the efficiency of the smart grid system with regard to monitoring, operation, and coordination/management purposes [56].

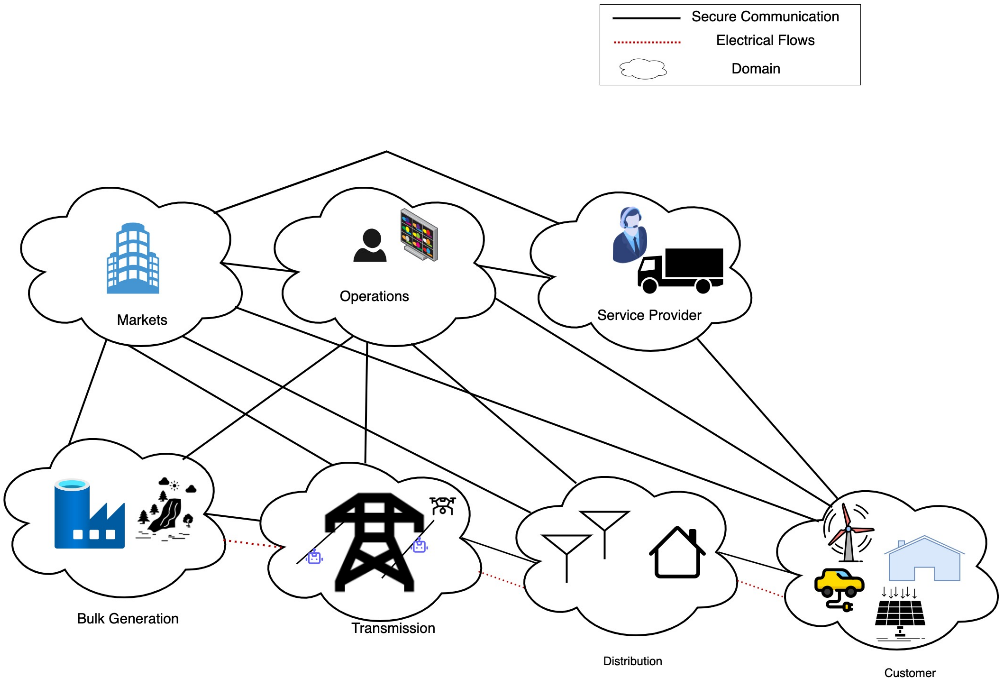

Figure 2. The Conceptual model of the Smart Grid [5,6].

The smart grid provides a number of efficient features in terms of power generation, supplies, distribution, and management, such as distribution automation, smart meters, distributed generation, renewable generation integration, automated and intelligent reviving systems, smart meter data coordination, secured communication, demand responses, reduced carbon emissions, the field area network (FAN), etc. These features would provide uninterrupted and effective power supply for the different applications of smart cities [57]. In addition, among the different applications of the smart grid in terms of communication, the crucial applications would be massive wireless connectivity for a huge number of devices (e.g., UAVs, robots, sensors, and IoT devices) and monitoring, the performance of secure communication for resource management and operation, and also the pursuit of real-time monitoring [52,53]. UAVs and robots are usually utilized for fault detection in transmission lines [52,53]. It is also difficult to maintain secured communication for operation and resource management, and also to perform time-critical or real-time operations of smart grids in the case of critical situations such as power outages, fault detection, island detection, etc. [58]. The technology of 6G is a suitable communication solution for fulfilling all of the smart grid communication network demands. The basic outline and fundamentals of 6G wireless communication are described in Section 1.3.

1.3. Overview of 6G Wireless Communication

The technology of 6G is the type of next-generation wireless communication that is capable of overcoming the shortcomings of previous 5G/4G wireless communication systems [9]. An intelligent 6G wireless communication network with improved KPIs will be expected to be implemented between 2027 to 2030 [59]. At present, autonomous systems are very familiar in every element of life such as healthcare, transportation, industry, etc. Thus, a massive number of sensors have been introduced into power grids, cities, homes, industries, vehicles, offices, and other sectors for automated and smart-driven lifestyles [9]. So, 5G can provide seamless wireless connectivity for such an autonomous system [24,60]. However, though 5G is already implemented in most countries, and it is going to be deployed all over the world within a few years, it cannot provide fully intelligent, reliable, and flexible communication with the required KPIs for the different applications of the smart grid [60,61]. Therefore, future 6G wireless communication is a suitable solution for satisfying the various demands associated with smart grid communication networks. [62].

It must be noted that 6G can provide remarkable performance improvement in the case of data rate, jitter, latency, reliability, connection density, area traffic capacity, spectral efficiency, flexibility, and energy efficiency for the effective execution of the considered major smart grid applications [7,62]. Moreover, 6G is a type of intelligent wireless communication that can provide vast possibilities, such as the augmentation of human intelligence, quality of experience, the Internet to everything, quality of life, etc. [63]. AI and 6G will create a revolution by transforming connected things into connected intelligence, which is appropriate for time-critical, secured, reliable, and adaptive smart grid applications [64].

Moreover, various novel technologies will be introduced in 6G wireless communication to effectively provide the required key performance indicators (KPIs) in terms of considered smart grid applications [1,65]. Non-orthogonal multiple access (NOMA); energy harvesting (EH); wireless power transfer (WPT); a green IoT; massive multiple-input–multiple-output (mMIMO); mmWave; terahertz (THz); AI-based ultra-dense networks (UDNs); intelligent reflecting surface (IRS); beamforming; AI-based secured edge/cloud computing; and device-to-device (D2D) communication are all examples of novel technology that can be used with 6G wireless communication to provide significant performance improvement in the case of the considered KPIs for smart grid systems (e.g., data rate, energy efficiency, jitter, area traffic capacity, latency, connection density, spectral efficiency, and reliability). These are all illustrated in Table 1 [1,7,63,65].

Table 1. Comparisons between the major KPIs of 5G and 6G [1,7,63,65].

KPIs	5G	6G
Peak Data Rate	20 Gbps	1 Tbps
Peak Spectral Efficiency	30 bps/Hz	60 bps/Hz
Experienced Data Rate	0.1 Gbps	1 Gbps
Energy Efficiency	0.5 pJ/b	1 pJ/b
Area Traffic Capacity	10 Mbps/m^2	1 Gbps/m^2
Latency	1 ms	10–100 µs
Jitter	Not Specified	1 µs
Connection Density	10^6 devices/Km^2	10^7 devices/Km^2
Reliability	10^{-5}	10^{-7}

1.4. Related Literature Overview and Key Motivations

Smart cities and smart grids are currently popular and highly researched topics in both academic and industrial sectors. Numerous works and publications have been dedicated to exploring the latest research trends and technological foundations in the smart grid communication networks of smart cities. A survey was published based on the multiple applications of IoT-Fog architectures for smart cities [66]. Moreover, the challenges of fog computing were also discussed in this paper. A recent survey on deep learning techniques in terms of privacy and the security enhancement of a smart grid network for a smart city was conducted [67]. A systematic cyberattack survey for various smart grid components through smart grid networks was described in [68]. The challenges and opportunities of smart grid communication networks were described in [2]. However, major 6G-enabled smart grid applications were not elaborately studied in [2]. The encompassing investigation of the latest research trends, as well as the technological foundations, in smart grid communication networks was described in [24,69]. In that study, the prospects of a next-generation intelligent smart grid based on AI, 5G, and the IoT was delved into. However, major 6G-enabled smart grid applications were not deeply investigated in [24,69]. Vulnerability assessments in terms of a massively connected CPS of 6G-enabled smart grid systems were described in [70]. A comprehensive survey of 6G in the case of only low-latency and secured applications of smart grid systems was described in [71]. In addition, 6G wireless communication that is incorporated into autonomous connected devices (ACDs) was also assessed in [72]. But smart grid applications by 6G wireless communication were not deeply studied in [72]. Table 2 summarizes the methodologies and limitations of some of these potential previous survey papers on smart grid networks.

Table 2. Methodologies and limitations of some potential previous survey papers on smart grids (SG) and smart cities (SC).

Methodologies	Limitations	Ref.
IoT-Fog architectures for smart cities	Focus on security and latency	[66]
DL based security for SG networks	Focus on security	[67]
Cyberattacks in SG components	Focus on cyberattacks and security	[68]
The role of 5G/6G in SC	Unexplored major 6G-enabled SG applications	[2]
Research trends of SG	Unexplored 6G-SG applications	[24,69]
Vulnerability assessment of SG	Security-centric SG applications	[70]
6G-based SG applications	Latency and security-centric SG applications	[71]
6G incorporated ACDs	SG applications were not deeply studied	[72]

Table 2 depicts the previous works that have primarily focused on security, vulnerability, and latency assessments of futuristic smart grid systems, as well as those that have discussed the technological foundations of smart grid communication networks with regard to 5G/6G wireless communication. However, they have not thoroughly examined the challenges related to massive connectivity and monitoring, secured communication for resource allocations and operations, and the time-critical operations of smart grid systems. Furthermore, the prospect of 6G wireless communication in the context of the abovementioned smart grid applications was not adequately investigated in the existing literature in terms of the novel communication technologies. This paper seeks to bridge this gap by exploring these critical aspects and shedding light on the potential of 6G technology for addressing the abovementioned challenges in smart grid applications.

1.5. Key Contributions of the Paper

The fundamental objective of this article is to illustrate an in-depth overview and potential of 6G wireless communication to perform the abovementioned applications and also to overcome the challenges of massive connectivity and monitoring, secured communication, and the time-critical operations of smart grid communication. Moreover, the prospects of 6G wireless communication in terms of the KPIs for the abovementioned smart grid applications are described in this survey paper. The required KPIs for the considered smart grid applications by utilizing the novel technologies of 6G are discussed elaborately in this article. In addition, the challenges and future research pathways in terms of 6G for the considered smart grid applications are also explained extensively here. This paper mainly emphasizes the 6G-based smart grid applications for the smart city. The principal contributions of this paper are outlined as follows:

- Section 2 is a description of the novel technologies of 6G for the respective KPI improvements for the considered smart grid applications.
- Section 3 represents the major applications of the smart grid that can be served by 6G wireless communication.
- Section 4 expresses the main challenges along with the potential future research pathways in the realm of 6G wireless communication for the considered smart grid applications.
- This study provides its conclusions in Section 5, and it also provides a concise overview of the key discoveries.

2. Novel Technologies of 6G for Smart Grid Applications

This section introduces the novel technologies of futuristic 6G communication for various smart grid applications. The future smart city and smart grid applications require a huge number of connected devices, as well as the performance of reliable, flexible, and time-critical operations [10,73]. The 6G-adopted new technologies that are required to enhance the KPIs and fulfill the requirements of smart grid communication networks are also discussed [10,73,74].

In this study, we consider massive connectivity, secured communication, and the time-critical monitoring and operations. Thus, various novel technologies will be introduced in 6G communication to address the specific requirements and challenges of smart grid systems. The novel technologies of 6G, such as WPT and EH, mMIMO, a green IoT, NOMA, mmWave, terahertz (THz), AI-based ultra-dense networks (UDNs), intelligent reflecting surface (IRS), device-to-device (D2D) communication, beamforming, and AI-based secured edge/cloud computing to provide significant performance improvement in case of the considered KPIs for smart grid system are reviewed [1,7,71,75–78]. Figure 3 illustrates the novel technologies regarding 6G wireless communication.

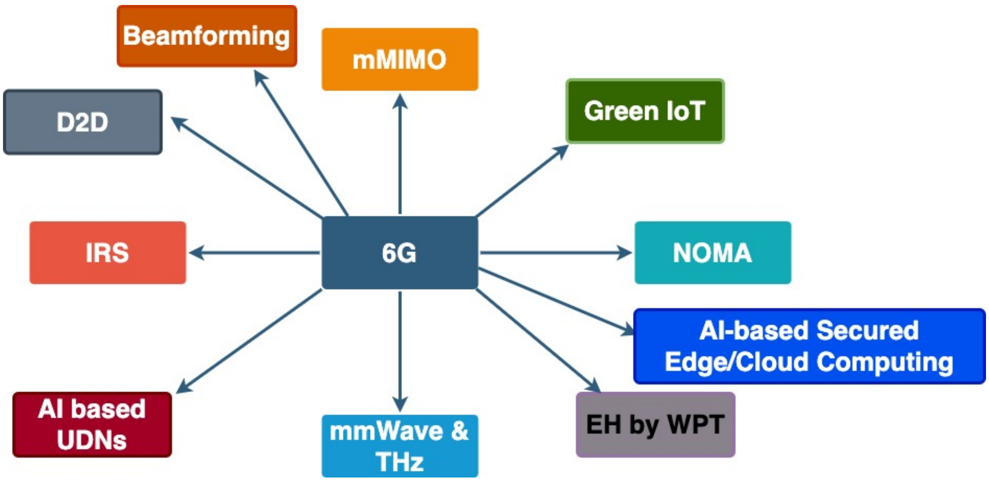

Figure 3. The novel technologies of 6G wireless communication and its respective KPIs.

2.1. Massive MIMO (mMIMO)

The fundamental principle of massive MIMO is to create multiple spatial channels between the BS and user devices by exploiting the spatial domain. Each antenna at the BS transmits signals simultaneously, and the user devices receive a combination of these signals, which are then isolated, as well as decoded at the receiver end by sophisticated techniques. In the traditional MIMO systems, both the user devices and BS have multiple antennas for throughput and reliability improvements. However, traditional MIMO-based wireless communication has a limited number of antennas at the user devices and BS.

In contrast, mMIMO significantly increases the number of BS antennas (i.e., in the order of tens or hundreds). Furthermore, mMIMO is a key performer in the case of 6G, which provides ultra-high speed data rates, along with low-latency and ultra-reliable communication. Moreover, MIMO enhances spectral efficiency, as well as energy efficiency [79,80]. The spectral efficiency is significantly improved due to the development of MIMO. Thus, mMIMO is incorporated with 6G wireless communication for spectral efficiency, capacity, and energy-efficient improvements [81].

2.2. Non-Orthogonal Multiple Access (NOMA)

NOMA provides enhanced spectral efficiency along with massive connectivity [1]. NOMA represents a multiple-access approach that is utilized in wireless communication systems. An individual user is assigned a specific orthogonal resource (e.g., time slots/frequency channels) to transmit their data in traditional orthogonal multiple access (OMA) schemes. However, NOMA takes a different approach by enabling multiple users to concurrently share identical resources. In NOMA, several users are allocated the same resources (e.g., time slots or frequencies), and the respective signals are decoded at the respective user end based on power levels, coding, or spreading sequences. This allows different users to access identical resources concurrently. Therefore, NOMA can provide enhanced spectral efficiency, and it can also serve a diverse number of users simultaneously. Moreover, it also provides enhanced data rates, as well as capacity, than is provided in conventional OMA techniques [82].

However, interference cancellation and signal decoding at the user ends are crucial issues for NOMA. The successive interference cancellation (SIC) technique is capable of solving the decoding and interference cancellation issues. Furthermore, orbital angular momentum (OAM) and MIMO are also incorporated with NOMA for the significant enhancement of spectral efficiency and capacity [83,84]. Nevertheless, full-duplex relaying (FDR) is combined with NOMA and OAM-MIMO techniques to enhance the coverage area, improve spectral efficiency, and mitigate the interference issues of FDR [85].

2.3. Energy Harvesting (EH) by Wireless Power Transfer (WPT)

The joint power and information transfer is a novel approach in providing energy harvesting and communication simultaneously through the wireless network [14]. Simultaneous wireless information and power transfer (SWIPT)-based NOMA (NOMA-SWIPT) is capable of serving massive connectivity, as well as enhanced spectral efficiency, data rates, reliability, and energy efficiency [86–88]. The SWIPT protocol is usually considered the best RF-based energy harvesting method for energizing the devices and overcoming the battery draining issue in the case of relaying and other purposes as well [87,89].

The cooperative relaying improves the coverage area and minimizes network outages for the cell edge devices [90,91]. Moreover, cooperative NOMA-enabled SWIPT protocols and an energy harvesting-based green IoT can provide improved spectral and energy efficiency, massive connectivity, wide coverage area, as well as low-latency communication [1,92].

2.4. mmWave and THz Communication

Furthermore, mmWave and THz technologies possess narrow beams and small wavelengths, leading to enhanced transmission speeds, increased throughput, improved spectral efficiency, and expanded capacity in 6G systems. In contrast, these waves have limited transmission distances.

The basic concept behind using mmWave and THz-based cells is to offer enhanced data rates, energy efficiency, capacity, and spectral efficiency while reducing latency. Achieving this involves minimizing the distance between the users and the BS, thereby reducing propagation loss and interference, as well as ensuring high-quality connections. Capacity and quality of service (QoS) are increased by integrating mMIMO with small cells. On the other hand, additive white Gaussian noise (AWGN) is reduced [93]. In addition, THz communication provides low-latency and broadband applications, like virtual reality (VR), ultra-HD videos, and augmented reality (AR).

2.5. AI-Based Ultra-Dense Networks (UDNs)

In this study, we explore the integration of AI techniques like reinforcement learning, deep learning, and machine learning in 6G-enabled UDNs for smart grid applications. The UDN is capable of handling a vast number of small cells. The fundamental concept behind deploying small cells is to ensure enhanced spectral efficiency, capacity, energy efficiency, and data rates while minimizing latency [1]. AI-based UDNs are another promising technology to meet the demands of modern communication systems by efficiently utilizing resources and enhancing connectivity. However, effective resource allocations and interference mitigation are the major difficulties in the case of UDNs.

Furthermore, effective resource allocation can be performed by applying AI in UDNs [94]. In addition, an AI-based UDN provides improved spectral and energy efficiency, network efficiency, and less jitter as well [1].

2.6. Intelligent Reflecting Surface (IRS)

In the wireless communications sector, intelligent reflecting surface (IRS) is a revolutionary emerging technology for the manipulation and utilization of radio waves. Also known as reconfigurable intelligent surfaces or smart reflecting surfaces, IRS is a passive array of electromagnetic elements, such as specially designed meta-materials or low-cost antennas, which can intelligently reflect, refract, and manipulate incoming wireless signals. IRS manipulates the transmission between sender and receiver in the case of a non-line-of-sight (NLOS) scenario. IRS controls the communication environment, as well as regulates the communication channels to improve performance [95].

IRS improves spectral efficiency, energy efficiency, and area capacity as well [96]. Moreover, IRS is also a promising and cost-effective solution for 6G.

2.7. Beamforming

Beamforming is a technique used in wireless communication systems to focus the radiated beam of radio frequency (RF) signal in a certain direction. A narrow and concentrated beam of energy can be directed in a certain direction by utilizing the beamforming technique. This directed beam enhances the signal strength and quality between a transmitter and receiver, thereby improving the overall communication performance. The omnidirectional radiation pattern of the cellular devices or BS can create severe interference, which can degrade the network performance. Thus, the beamforming technique is introduced in modern cellular technology as it can radiate a beam to a particular device in a directional manner [81]. AI can also be integrated with beamforming techniques to improve efficiency [97].

Therefore, it can provide faster, more reliable, and interference-free communication. Moreover, the spectral efficiency is improved due to interference minimization [1].

2.8. AI-Based Secured Edge/Cloud Computing

The current cloud and edge computing frameworks are not capable of processing huge numbers of small data sets, as they are designated to handle big data sets. To overcome this drawback, next-generation 6G communication networks will require AI-based edge computing infrastructure to appropriately process such vast quantities of small data. This will necessitate the development of new machine learning methods that go beyond the traditional big data analysis approach [8]. These advanced AI-based techniques will have a vital role in enhancing network functions, as well as enabling the provision of novel services to reduce the processing delay of the edge devices envisioned for future communication networks [8]. In the future, network configurations will emphasize energy efficiency improvement when offloading substantial volumes of small data to edge computing centers.

Ensuring data privacy and security in current IoT-based networks is a crucial priority. The Internet of Everything (IoE) interconnects a huge number of devices. Thus, the need for decentralized AI technologies becomes evident to train data sets that are spread unevenly across multiple edge/cloud devices for IoE networks. However, this distributed approach also introduces potential security vulnerabilities, including poisoning attacks and authentication issues [98].

The integration of AI and the blockchain is a potential solution in which to address the abovementioned challenges. Future communication networks must incorporate adaptive security solutions based on AI and blockchain principles [76,99]. These advanced security measures will play a critical role in securing IoE networks from potential threats and ensuring the transmitted data integrity, security, as well as the process, across the communication network [8]. The novel technologies of 6G wireless communication provide significant improvements in KPIs for various applications. However, future network technologies will raise concerns about cost, security, and privacy [98,100]. The technology of 6G can address security issues by introducing AI, the blockchain, and federated learning (FL) [76,77,99]. Blockchain-incorporated FL prevents malicious activities that can persist in conventional blockchain-based applications. Moreover, the introduction of appropriate algorithms for blockchain- and FL-based 6G networks could provide significant security and privacy enhancements for various applications [98,100].

2.9. Device-to-Device (D2D) Communication

D2D communication defines a communication architecture that facilitates direct communication among adjacent devices, except in traditional BSs or infrastructure intermediaries. In D2D communication, devices, such as smartphones, tablets, or IoT devices, can communicate directly with each other, forming ad hoc networks or forming a direct link when they are in close proximity.

D2D communication reduces the gap between the sender and receiver. Moreover, it can enhance the battery life of the device as well [1]. The spectral efficiency can be improved by introducing mMIMO for D2D communication. Moreover, D2D also provides low-latency communication by maintaining machine-to-machine communication [101].

2.10. Key Findings of the Novel Technologies and Their Relation to the Smart Grid

The evidence presented above clearly indicates that 6G is capable of providing significantly improved KPIs than prior generations (e.g, 5G, and 4G) of wireless communication. This is made possible through the utilization of various emerging and innovative technologies. In addition, the achieved improved KPIs by the respective novel techniques of 6G are summarized in Table 3.

Table 3. Improved KPIs by the respective novel techniques of 6G.

Novel Technologies	Achieved KPIs	References
mMIMO	Improved SE, capacity, EE	[79–81]
NOMA	Improved connection density, data rate, SE	[82–85]
EH by WPT	Environmentally friendly, improved SE, EE	[1,86–89]
mmWave and THz	Improved data rate, capacity, SE, EE, low latency	[1,93]
AI-based UDNs	Improved network efficiency, EE, SE, low jitter	[1,94]
IRS	Improved SE, EE, area capacity	[95,96]
Beamforming	Improved SE, EE, less power consumption	[81,97]
AI-based secured edge/cloud computing	Improved EE, enhanced security	[8,76,99]
D2D communication	Improved SE and EE	[1,101,102]

To address the essentials of the considered smart grid applications, appropriate wireless communication is required that supports time-critical operations, as well as secure and massive connectivity. The essentials of the considered smart grid applications are fulfilled by 6G wireless communication. The forthcoming section will delve into a detailed discussion of how 6G addresses these crucial aspects.

3. Major Applications of the Smart Grid Served by 6G

The smart grid holds immense significance for the advancement of the sustainable smart city. The key features of the smart grid communication network are its reliance on high speed, reliability, low latency, low jitter, flexibility, massive connectivity, higher area capacities, computational offloading, and secure data communication networks to effectively and intelligently manage complex power systems. Unlike traditional power grids, smart grids employ bidirectional communication, which greatly enhances their capabilities [102]. However, the specific communication demands and appropriate techniques can vary based on the particular environment and circumstance.

Figure 4 illustrates the flowchart regarding the operation logic and framework for implementing a smart grid by 6G. The goal and objectives of the smart grid communication network for the smart city applications are defined, such as massive connectivity and monitoring, secured communication for operation and resource management, and time-critical operations. The 6G-enabled smart grid infrastructure is designed based on these major requirements. The requirements are considered based on the goal and objectives of the smart grid for smart city applications. Afterward, all the requirements based on the objectives are verified. Subsequently, 6G-enabled smart grid infrastructure is deployed and integrated into the control and monitoring system. Afterward, the smart grid functionalities are tested and validated. The monitoring and management of a smart grid by 6G-enabled wireless communication is also performed accordingly, as is depicted in Figure 4.

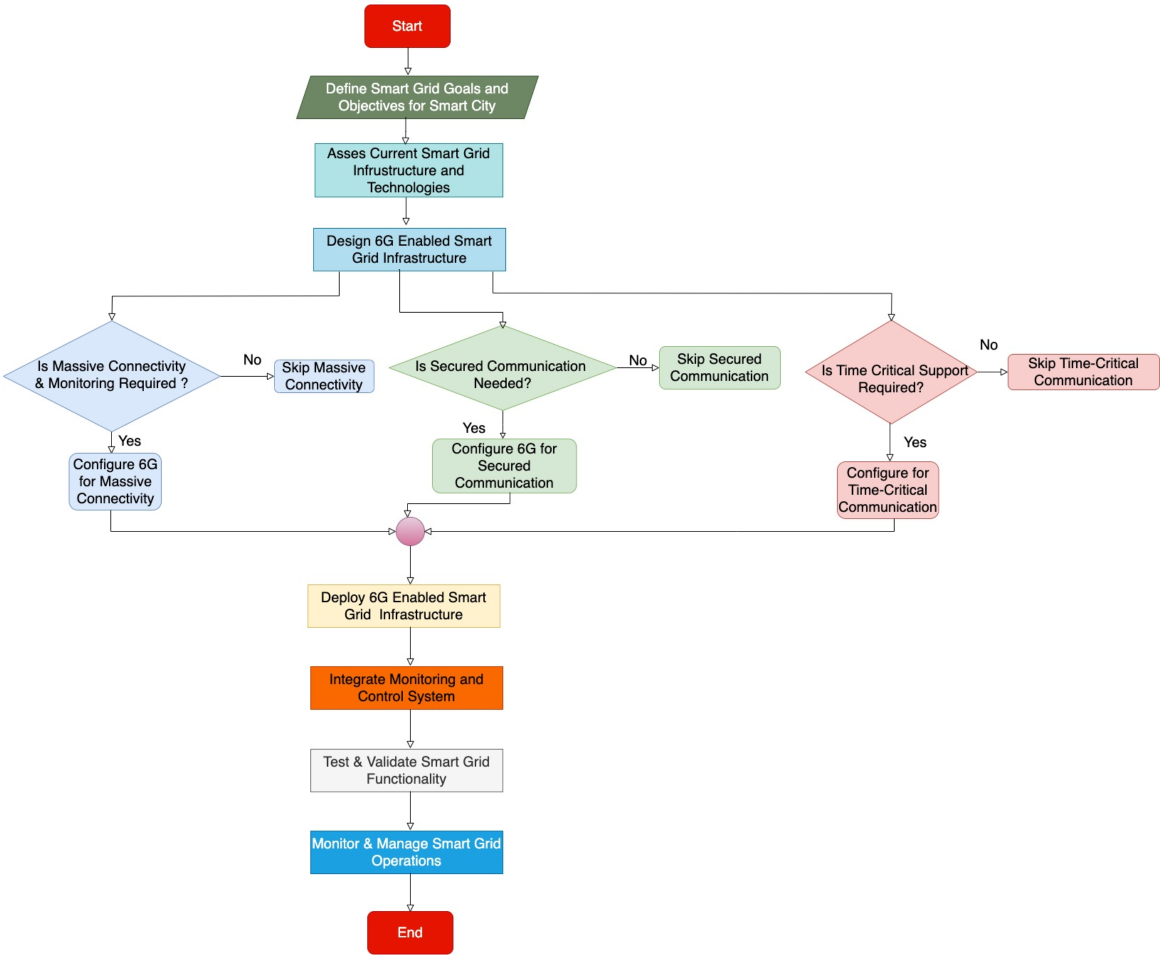

Figure 4. Flowchart of a 6G-Enabled Smart Grid.

At present, low carbonization is one of the prime concerns for the power grid systems of smart cities [103]. The integration of 6G and a smart grid is a suitable solution for enhancing the coordinated operation of the smart grid by a damping technique for low carbonization. A 6G-enabled smart grid can provide real-time monitoring and a control of energy flows. Moreover, the integration of 6G and a smart grid can also provide enhanced energy efficiency, reduction in carbon emissions, and the support of sustainable energy practices. In addition, this synergy provides real-time grid condition monitoring, demand responses, wide-area monitoring and control, advanced control, and efficient load management by the massive, high-speed, and low-latency 6G wireless communication. Grid resilience, cybersecurity, and supportive policies play critical roles in ensuring a sustainable and reliable smart grid ecosystem by utilizing sustainable, secured, and reliable 6G wireless communication. The technology of 6G could have a significant impact on the various applications of smart grid systems. This paper mainly focuses on massive connectivity and monitoring, secured communication for operations and resource management, and the time-critical operations of smart grid systems. The major applications and respective novel techniques are mentioned in the following subsections.

3.1. Massive Connectivity and Monitoring

The technology of 6G wireless communication is a feasible solution for massive connectivity and the time-critical monitoring of smart grid systems. Furthermore, 6G can provide seamless communication among a massive number of devices, thereby facilitating real-time data exchange, comprehensive time-critical monitoring, and effective energy management. For time-critical monitoring, along with massive connectivity, the important KPIs are connection density, area traffic capacity, data rate, reliability, latency, energy efficiency, and spectral efficiency. PD-NOMA offers notable performance and advantages that facilitate enhanced data rates, spectral efficiency, massive connectivity, as well as low latencies to support massive connectivity along with the time-critical monitoring of smart grid systems [104]. In PD-NOMA, distinct transmission powers are assigned to multiple users according to their respective channel conditions. The superimposed signal, containing data for all users, is then transmitted to them [105]. Based on the reception and channel condition, the users employ SIC or direct decoding to decode their respective signal. The SIC decodes the signal of individual users sequentially from the superimposed signal based on their assigned power [106]. Therefore, PD-NOMA, along with OAM-MIMO (NOMA-OAM-MIMO), can provide massive connectivity, high data rates, and improved spectral efficiency. Moreover, IRS, THz, and BF can be incorporated with the D2D/cooperative relay-based NOMA-OAM-MIMO communication for smart grid UDNs to provide improved reliability, low latency, less power consumption, enhanced area capacity, and an enhanced coverage area of the UDNs of a smart grid [81,83,84,90,91,93,95–97,101]. Furthermore, NOMA-enabled Q-learning UDNs can also provide high area capacities and massive connectivity for the UDNs of a smart grid system [94,107]. In addition, energizing the massive number of connected devices is another challenging issue. Thus, NOMA-incorporated wireless power transfers, such as NOMA-SWIPT, are required. They are needed to energize the IoTs, UAVs, robots, and edge/cloud devices, as well as provide energy efficiency [14].

The grid monitoring algorithms (e.g., PLeC/AB-PLeC/FIB/BW-PLeC) can be processed by AI-based edge/cloud computing devices 8. The energy devices (e.g., IoTs, UAVs, and robots) can communicate with the edge/cloud devices via the abovementioned novel techniques of 6G wireless communication system for time-critical smart grid monitoring [108,109]. The fault identification/location, as well as the deployment of the phasor measurement unit (PMU), are vital factors for grid monitoring [108]. For medium voltage grids, along with low latency monitoring, three different algorithms (path length constraint (PLeC), the application-level betweenness, along with PLeC (AB-PLeC), as well as the flow interference and bandwidth constraint (FIB)) were proposed in [108]. These algorithms are mainly focused on the strategic deployment of high-capacity links, thus aiming to strike a trade-off between deployment expenses and the achieved latency. The PLeC along with bandwidth and path length constraint (BW-PLeC) algorithms are introduced to achieve a low-latency communication framework [109]. These algorithms aim to enhance the performance of the conventional power-line communication technique by incorporating alternative enhanced speed communication links at crucial locations of the smart grid. The primary goal is to meet the specific delay requirements while minimizing deployment costs. All the requirements of the monitoring algorithms can be fulfilled by the abovementioned novel communication techniques of 6G.

3.2. Secured Communication for Operations & Resource Management

The interconnection, reconfigurability, the wide variety of energy device types, and information networks introduce crucial implications for data security and reliability in smart grid systems [110–112]. Therefore, a massive amount of data are generated in case of bidirectional smart grid communication, and proper security and privacy are required for the operational and other confidential instances of data [26,113,114]. The operational integrity of the smart grid could be compromised by covert cyberattacks or the manipulation of data [115].

Thus, advanced encryption, authentication, and privacy mechanisms are required to protect the critical data transmitted between smart grid devices and control centers. In traditional artificial intelligence of things (AIoT) frameworks, vast amounts of identical energy-oriented data from the IoT devices of each user are transferred to cloud/edge devices for storage or decentralized processing [116]. However, this approach poses significant risks in terms of privacy infringement and potential data misuse. Federated learning (FL) is an attractive AI paradigm that ensures privacy while preserving data [116,117]. The energy data owners (EDOs) can collectively train the shared AI model, except in cases of divulging the energy-oriented data by an edge-cloud-assisted FL framework [99,117]. It facilitates efficient and fortified energy data communication for the respective smart grid users by integrating FL and the blockchain [99]. Furthermore, to address the challenge of limited knowledge regarding confidential multidimensional user data in real-world cases, a bi-layer deep re-enforcement-learning-inspired incentive algorithm is also introduced in [99]. This algorithm incentivizes active participation from energy data owners (EDOs), as well as encourages high-quality contributions to the shared model.

The software-defined IoT (SDIoT) in 6G makes the CPS more vulnerable to cyberattacks [62]. A novel graphics-processing-unit (GPU)-based adaptive robust state estimator named LSTMKF was introduced in [62]. This state estimator integrates a deep learning algorithm, and is specifically based on long short-term memory (LSTM) with an extended nonlinear Kalman filter. By combining these techniques, the LSTMKF state estimator enhances security measures and effectively manages the load within the system [62]. Edge computing is required for the computational offloading of LSTMKF due to computational complexity. However, the lightweight false state injection (FSI) can poison the state information of the edge devices in the case of deep-learning-based resource allocation [94]. Thus, to enhance security and privacy, an FL with the blockchain can be integrated for edge computing-based distributed computational offloading, as well as in also enhancing energy efficiency [99,116,117]. Moreover, the edge/cloud devices can be energized by the NOMA-SWIPT-based technique, which is discussed in an earlier subsection [14].

3.3. Time-Critical Operations

The real-time operations of smart grid systems, such as fault detection, outage management, island detection and management, energy management, and load balancing, can be supported by 6G. The network slicing based on non-real-time, close-to-real-time, and real-time operations is an effective solution for smart grid systems [118]. The time-critical applications of smart grid systems require area traffic capacity, spectral efficiency, latency, user data rate, and reliability. The novel 6G-enabled D2D/cooperative NOMA-OAM-MIMO, along with IRS, BF, THz, AI-based edge computing, and the real-time smart grid operational algorithms (e.g., EDGE/PMU-based voltage stability/phase-angle based island detection/learning-to-infer), can fulfill the KPI requirements and can also perform the time-critical operations of smart grids [119–122]. Furthermore, wireless power transfer (SWIPT/NOMA-SWIPT) can energize edge/cloud devices for time-critical operational purposes, which is discussed in the earlier subsection of this paper. Moreover, the emBB and mMTC are suitable for non-real-time applications, and mMTC is appropriate for semi-real-time applications and ultra-reliable-low-latency-communication (URLLC). Both are appropriate for time-critical (real-time) smart grid operations [118]. The time-sensitive communication service-based AI-enabled 6G network slicing approach is a possible solution for accomplishing the time-critical smart grid operations [118].

For the time-critical smart grid operations, there are several novel algorithms that have been proposed for time-critical energy management, island detection, and outage detection and recovery. The energy management of the smart grid system regarding the demand response is a time-critical issue that can be overcome by a hybrid EDGE algorithm [119]. Edge is evolved by combining a genetic algorithm (GA) along with an enhanced differential evolution (EDE) algorithm [119]. The phase angle-based island detection method is much more resilient, more secure, computationally simple, and takes less time to detect the island of a smart grid system [123]. The PMU-based voltage instability indexed method was introduced in [120]. The proposed index can also detect the outage of lines/gens in an unsupervised manner [120]. The AI-enabled network slicing and intelligent cloud/edge computing can also overcome the computational issue within the provided time constraint for the proposed technique. The real-time detection of line outages is an immensely challenging task, particularly in scenarios where unknown line outages rapidly accumulate, thus leading to large-scale blackouts [121]. Hence, a pioneering learning-to-infer approach has been devised to detect the time-critical multi-line outages in a smart grid [122]. Additionally, the integration of AI-edge computing and 6G wireless communication techniques can effectively tackle the computational complexity involved in the process. Moreover, 6G-based novel communication techniques, which are mentioned above along with AI-enabled network slicing and intelligent edge/cloud computing, can process the algorithms for computational offloading, as well as effectively perform the time-critical operations of smart grids.

Based on the above discussion, Table 4 summarizes the major applications and respective suitable techniques for 6G-based smart grid communication networks.

Table 4. The major application and respective suitable techniques for 6G-based smart grid communication networks.

Major Applications	Techniques
Massive connectivity	D2D/cooperative PD-NOMA with IRS, beamforming, THz, AI-based edge computing, Q-learning
Monitoring	PMU/PLeC/AB-PLeC/FIB/BW-PLeC
Energized massive connected devices	NOMA-SWIPT
Security and privacy	FL and blockchain
Reducing vulnerabilities	Edge-cloud-assisted FL, the blockchain, and LSTMKF
Energized edge/cloud devices	NOMA-SWIPT
Time-critical communication	D2D/cooperative PD-NOMA with IRS, beamforming, THz, AI-enabled network slicing, AI-based edge computing
Real-time energy load balancing	EDGE algorithm
Unsupervised voltage stability	PMU-based index
Real-time island detection	Phase-angle based detection
Real-time line outage detection and recovery	Learning-to-infer approach
Energized edge/cloud devices	NOMA-SWIPT

4. Challenges and Future Research Directions

It must be noted that 6G can provide the required KPIs for the considered smart grid applications. However, there are some challenges that will be discussed in the following subsection, along with future research directions for the relevant challenges.

4.1. THz and mmWave Communication Challenges

The utilization of THz waves for wireless communication faces a significant challenge due to its substantial free space path loss (FSPL). Thus, THz/mmWave provides limited wireless coverage or transmission distance. However, larger lenses and antennas could potentially reduce FSPL issues, but they are not ideal because they conflict with the crucial design parameter of maintaining a compact form factor for indoor network components [124].

Additionally, the high directivity of the link makes it susceptible to blockage issues [125]. To address these challenges, beam-forming technology can be employed to mitigate blockage vulnerability. However, reliable non-line-of-sight (NLOS) wireless communication can be ensured by relay/IRS. It is essential to find potential solutions that overcome the major challenges of IRS/relay, such as beamforming, signal reception, location, etc., for the successful implementation of THz wave-based wireless communication systems.

4.2. Energy Consumption and Low-Carbon Emission Challenges

The deployment of UDNs results in a massive consumption of energy. The mobile network operators face a considerable financial burden, with approximately 30% of their operational expenses (OPEX) being attributed to energy consumption [126]. Moreover, BSs

predominantly rely on the electrical national power grid, which, unfortunately, is powered by methods that generate CO_2 emissions, as documented in [127].
WPT is a viable solution for overcoming these challenges. Moreover, there are other suitable techniques to overcome the energy consumption issues of UDNs, such as optimization of the radio process, radio planning and deployment, hardware solutions, and the BS sleeping strategy [128]. More future research needs to be conducted on the abovementioned AI-based techniques for performance optimization.

4.3. Network Management and Orchestration

Different applications of smart grid systems require specific network slices in the case of 6G. Therefore, 6G needs to deal with heterogeneous network slices for different applications, as well as those that are crossed with multiple technical domains, such as radio access, cloud, core, and edge networks. Thus, intelligent network management and orchestration techniques are required for the use of a 6G wireless network in a smart grid system.

Zero-touch service management and intelligent networks can be a feasible solution for the intelligent and autonomous network orchestration and management techniques for 6G [129]. Different applications are considered in this technique but smart grid applications should still be well studied. In addition, more ongoing research and studies are required for network management and orchestration techniques.

4.4. 3D Network Coverage for UAVs and Monitoring Robots

It is very challenging to achieve three-dimensional (3D) network coverage for UAVs and monitoring robots in 6G-enabled smart grids with respect to fault monitoring in transmission lines and towers. The enhanced data rate, low latency, and reliable wireless network coverages are needed for UAVs and monitoring robots. Moreover, mobility is another big challenge for uninterrupted communication between ground offices and UAVs/robots [7].

UAV swarm-incorporated cell-free wireless communication is a potential solution for 3D network coverage regarding the monitoring of UAVs and robots [7]. Moreover, UAV-based base stations can also provide network coverage in remote areas where transmission lines and towers are located [7]. A number of ongoing studies are required on AI-based UAV swarms that can provide more effective network coverage and transmission line monitoring. Moreover, a number of future studies on UAVs to everything (U2X) and cell-free 6G wireless communication are required to overcome the mobility issue of monitoring UAVs/robots [130].

4.5. Ultra-High Capacity Backhaul Link

The technology of 6G can provide a thousand times higher wireless connectivity than 5G. To provide a high data rate, high area capacity, and high connection density for the wireless communication of smart grid networks, the backhaul connectivity should cope with a high capacity to support the huge amounts of traffic [9]. Ultra-high capacity backhaul refers to the high-speed and high-capacity links that connect the core network or central hub of a telecommunications system to the access points or base stations in the network. Backhaul is a critical part of the network infrastructure as it is responsible for carrying a high volume of data traffic between the core and edge of the network.

Thus, various emerging technologies such as free space optical communication (FSO), high-speed fiber optics, and OAM-based backhaul communication can be potential solutions through which to provide high traffic capacity for huge volumes of traffic for smart grid networks [9,131,132]. A number of studies are required for reliable, efficient ultra-high capacity, and ultra-high speed FSO/OAM communication for 6G networks.

4.6. Appropriate Channel Estimation Techniques

In 6G, IRS emerged has emerged as a viable solution through which to address the primary challenges, including high cost, limited coverage, and excessive power consumption, of previous wireless communication generations. The integration of mMIMO, AI-enabled beamforming, and IRS technologies effectively reduces propagation loss and enhances the overall QoS.

However, implementing efficient channel estimation for the wireless link between the BS and IRS poses several challenges. Among these challenges, dealing with the randomness inherent in the real channel is particularly difficult. To overcome this, a deep learning approach can be introduced to enable adaptive collaboration between the BS and IRS during channel estimation.

Moreover, channel estimation is essential for the EH-based NOMA-SWIPT technique [133]. Without appropriate channel estimation, it is very challenging to maintain flawless communication, as well as energizing the end devices.

Therefore, AI can be incorporated with 6G wireless communication to provide accurate channel estimation for uninterrupted communication, as well as energy harvesting in end devices. In addition, appropriate channel estimation algorithms need to be developed and incorporated in 6G-based smart grid communication networks to fulfill these objectives.

4.7. Suitable Physical Layer Security

Securing a UDN consisting of diverse node types becomes a prime concern in which to achieve flexible quantum-safe security measures for 6G. Due to these considerations, a bottom-up method is advocated, thereby aiming to harness all available security measures across the generic communication stack. A pivotal technology candidate in this endeavor are the potential lattice-based signature schemes [134].

Moreover, various techniques such as secure beamforming, physical layer encryption, and authentication mechanisms have been proposed in previous studies to protect smart grid communication from eavesdropping and unauthorized access [135]. As 6G aims to offer a comprehensive security approach, it is imperative to not only focus on security by design, but to also address privacy by design. Both aspects are essential for providing a robust and trustworthy 6G wireless communication system for smart grid monitoring and operations.

4.8. Challenges of Interference and Effective Spectrum Management

Different interference mitigation techniques such as parallel interference cancellation and SIC can be integrated with a 6G-based smart grid network. In addition, deep learning-based decoding can be incorporated with NOMA-enabled 6G wireless communication instead of SIC to provide faster and more effective decoding of the respective end user signal without interference [136]. However, more feasible solutions are required for some open challenges of NOMA, such as multi-cell scenarios, mobility, imperfect channel state information, etc.

The limited spectrum resources, along with interference mitigation challenges, require the effective management of 6G. Different spectrum-sharing approaches such as implementing spectrum sharing strategies and prolific spectrum management techniques are appropriate for 6G spectrum management. Ensuring efficient spectrum management is critical for optimal resource exploitation while maximizing the QoS for users [9].

In addition, different suitable spectrum handling techniques can be incorporated with 6G-based smart grid communication networks, such as wide-spectrum access, carrier aggregation, and cognitive radio [9].

4.9. Challenges for Energy Optimization Algorithms, Energy Flow, and Traffic Flow Algorithms

It must be noted that 6G wireless communication for smart grid applications must meet specific requirements, including ultra-low latency, high reliability, data rates, edge computing, security, energy efficiency, and adaptable QoS. Challenges include interoperability, scalability, regulatory compliance, and resilience. Balancing these requirements and overcoming challenges is crucial for the successful integration of 6G into smart grid energy optimization and traffic flow algorithms.

5. Conclusions

In this paper, the integration of 6G technologies presents a transformative opportunity through which to revolutionize the energy sector through smart grids in terms of energizing the key enablers of smart cities. This paper has demonstrated the potential of 6G wireless communication in enabling time-critical smart grid applications with massive connectivity and enhanced security by improved KPIs and novel technologies of next-generation intelligent wireless communication.

Nevertheless, numerous significant challenges are associated with 6G-enabled smart grid network implementation. These challenges encompass limitations in THz and mmWave communication, energy consumption optimization, network management, 3D network coverage, ultra-high capacity backhaul links, channel estimation, physical layer security, and interference management. Addressing these obstacles necessitates interdisciplinary research, collaboration, and innovative solutions. In addition, future research directions have been outlined in this paper to overcome these challenges and to harness the full potential of 6G in smart grid communication networks. By effectively addressing these issues, we can unlock the capabilities of 6G, as well as aim to create intelligent, interconnected, and resilient smart grid systems.

In conclusion, continuous research and innovation are crucial to fully harness the transformative power of 6G technologies for smart grid applications. With concerted efforts and advancements in these areas, we can propel the energy sector of smart cities toward a more sustainable, efficient, and intelligent future.

Author Contributions: Conceptualization, A.A.A. and W.S.; visualization, A.A.A.; writing—original draft preparation, A.A.A., J.H., V.-H.B., and W.S.; writing—review and editing, A.A.A., J.H., V.-H.B., and W.S.; supervision, A.A.A. and W.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations were used in this manuscript:

ACD	Autonomous connected devices
6G	Sixth generation
BSs	Base stations
KPIs	Key performance indicators
IoT	Internet of things
IoE	Internet of everything
AI	Artificial intelligence
CPS	Cyber physical system
UAV	Unmanned aerial vehicle
OSN	Online social networking
mMIMO	Massive multiple-input–multiple-output
mmWave	Millimeter wave
NOMA	Non-orthogonal multiple access
EH	Energy harvesting
WPT	Wireless power transfer

Green IoT	Green Internet of things
FAN	Field area network
THz	Terahertz
IRS	Intelligent reflecting surface
D2D	Device-to-device
SWIPT	Simultaneous wireless information and power transfer
RF	Radio frequency
UDNs	Ultra-dense networks
LOS	Line of sight
AR	Augmented reality
FL	Fedarated learning
VR	Virtual reality
UAVs	Unmanned aerial vehicles
PD-NOMA	Power domain non-orthogonal multiple access
SIC	Successive interference cancellation
PMU	Phasor measurement unit
PLeC	Path length constraint
AB-PLeC	Application-level betweenness and path length constraint
FIB	Flow Interference and bandwidth constraint
BW-PLeC	Bandwidth and path length constraint
QoS	Quality of service
EDOs	Energy data owners
FSI	False state injection
CPS	Cyber physical system
LSTMKF	Long short-term memory Kalman filter
FSPL	Free space path loss
NLOS	Non-line-of-sight
FSO	Free space optical communication
OAM	Orbital angular momentum
OPEX	Operational expenses
CO_2	Carbon dioxide
V2V	Vehicle-to-vehicle
V2I	Vehicle-to-infrastructure
V2X	Vehicle-to-everything
V2G	Vehicle-to-grid
V2P	Vehicle-to-pedestrian
V2C	Vehicle-to-cloud
V2D	Vehicle-to-device

References

1. Cui, J.; Ding, Z.; Fan, P. Beamforming Design for MISO Non-Orthogonal Multiple Access Systems. *IET Commun.* **2016**, *11*, 720–725. [CrossRef]
2. Shehab, M.; Khattab, T.; Kucukvar, M.; Trinchero, D. The Role of 5G/6G Networks in Building Sustainable and Energy-Efficient Smart Cities. In Proceedings of the 2022 IEEE 7th International Energy Conference (ENERGYCON), Riga, Latvia, 9–12 May 2022; pp. 1–7. [CrossRef]
3. Ma, R.; Chen, H.-H.; Huang, Y.-R.; Meng, W. Smart Grid Communication: Its Challenges and Opportunities. *IEEE Trans. Smart Grid* **2013**, *4*, 36–46. [CrossRef]
4. Panda, D.K.; Das, S. Smart Grid Architecture Model for Control, Optimization and Data Analytics of Future Power Networks with More Renewable Energy. *J. Clean. Prod.* **2021**, *301*, 126877. [CrossRef]
5. Fadel, E.; Gungor, V.C.; Nassef, L.; Akkari, N.; Malik, M.A.; Almasri, S.; Akyildiz, I.F. A Survey on Wireless Sensor Networks for Smart Grid. *Comput. Commun.* **2015**, *71*, 22–33. [CrossRef]
6. van der Kam, M.; Bekkers, R. Mobility in the Smart Grid: Roaming Protocols for EV Charging. *IEEE Trans. Smart Grid* **2023**, *14*, 810–822. [CrossRef]
7. NIST Framework 2.0. Roadmap for Smart Grid Interoperability Standards [online]; National Institute of Standards and Technology. 2010. Available online: https://www.nist.gov/system/files/documents/smartgrid/NIST_Framework_Release_2-0_corr.pdf (accessed on 3 October 2023).
8. Alwis, C.D.; Kalla, A.; Pham, Q.V.; Kumar, P.; Dev, K.; Hwang, W.J.; Liyanage, M. Survey on 6G Frontiers: Trends, Applications, Requirements, Technologies and Future Research. *IEEE Open J. Commun. Soc.* **2021**, *2*, 836–886. [CrossRef]

9. Wang, C.-X.; You, X.; Gao, X.; Zhu, X.; Li, Z.; Zhang, C.; Hanzo, L. On the Road to 6G: Visions, Requirements, Key Technologies, and Testbeds. *IEEE Commun. Surv. Tutor.* **2023**, *25*, 905–974. [CrossRef]
10. Chowdhury, M.Z.; Shahjalal, M.; Ahmed, S.; Jang, Y.M. 6G Wireless Communication Systems: Applications, Requirements, Technologies, Challenges, and Research Directions. *IEEE Open J. Commun. Soc.* **2020**, *1*, 957–975. [CrossRef]
11. Song, Y.; Wan, C.; Hu, X.; Qin, H.; Lao, K. Resilient Power Grid for Smart City. *iEnergy* **2022**, *1*, 325–340. [CrossRef]
12. Konstantinou, C. Toward a Secure and Resilient All-Renewable Energy Grid for Smart Cities. *IEEE Consum. Electron. Mag.* **2022**, *11*, 33–41. [CrossRef]
13. Masera, M.; Bompard, E.F.; Profumo, F.; Hadjsaid, N. Smart (Electricity) Grids for Smart Cities: Assessing Roles and Societal Impacts. *Proc. IEEE* **2018**, *106*, 613–625. [CrossRef]
14. Kizilkaya, B.; Zhao, G.; Sambo, Y.A.; Li, L.; Imran, M.A. 5G-Enabled Education 4.0: Enabling Technologies, Challenges and Solutions. *IEEE Access* **2021**, *9*, 166962–166969. [CrossRef]
15. Hu, S.; Chen, X.; Ni, W.; Wang, X.; Hossain, E. Modeling and Analysis of Energy Harvesting and Smart Grid-Powered Wireless Communication Networks: A Contemporary Survey. *IEEE Trans. Green Commun. Netw.* **2020**, *4*, 461–496. [CrossRef]
16. Smart Vehicles and 5G Mobile Transport-Use Case. Available online: https://www.ericsson.com/en/cases/2016/smart-vehicles-and-transport (accessed on 3 October 2023).
17. Hobert, L.; Festag, A.; Llatser, I.; Altomare, L.; Visintainer, F.; Kovacs, A. Enhancements of V2X Communication in Support of Cooperative Autonomous Driving. *IEEE Commun. Mag.* **2015**, *53*, 64–70. [CrossRef]
18. Gupta, N.; Juneja, P.K.; Sharma, S.; Garg, U. Future Aspect of 5G-IoT Architecture in Smart Healthcare System. In Proceedings of the 2021 5th International Conference on Intelligent Computing and Control Systems (ICICCS), Madurai, India, 6–8 May 2021; pp. 406–411.
19. Saad, M.M.; Khan, M.T.R.; Shah, S.H.A.; Kim, D. Advancements in Vehicular Communication Technologies: C-V2X and NR-V2X Comparison. *IEEE Commun. Mag.* **2021**, *59*, 107–113. [CrossRef]
20. Kaiser, M.S.; Ray, K.; Bandyopadhyay, A.; Jacob, K.; Long, K.S. (Eds.) *Proceedings of the Third International Conference on Trends in Computational and Cognitive Engineering: TCCE 2021, Parit Raja, Malaysia, 21–22 October 2022*; Springer Nature: Berlin/Heidelberg, Germany, 2022.
21. Neirotti, P.; De Marco, A.; Cagliano, A.C.; Mangano, G.; Scorrano, F. Current Trends in Smart City Initiatives: Some Stylised Facts. *Cities* **2014**, *38*, 25–36. [CrossRef]
22. Kunzmann, K.R. Smart Cities after COVID-19: Ten Narratives. *disP-Plan. Rev.* **2020**, *56*, 20–31. [CrossRef]
23. Zygiaris, S. Smart City Reference Model: Assisting Planners to Conceptualize the Building of Smart City Innovation Ecosystems. *J. Knowl. Econ.* **2013**, *4*, 217–231. [CrossRef]
24. Esenogho, E.; Djouani, K.; Kurien, A.M. Integrating Artificial Intelligence Internet of Things and 5G for Next-Generation Smartgrid: A Survey of Trends Challenges and Prospect. *IEEE Access* **2022**, *10*, 4794–4831. [CrossRef]
25. Neffati, O.S.; Sengan, S.; Thangavelu, K.D.; Kumar, S.D.; Setiawan, R.; Elangovan, M.; Mani, D.; Velayutham, P. Migrating from Traditional Grid to Smart Grid in Smart Cities Promoted in Developing Country. *Sustain. Energy Technol. Assess.* **2021**, *45*, 101125.
26. Dileep, G.J. A Survey on Smart Grid Technologies and Applications. *Renew. Energy* **2020**, *146*, 2589–2625. [CrossRef]
27. Adnan, M.; Ghadi, Y.; Ahmed, I.; Ali, M. Transmission Network Planning in Super Smart Grids: A Survey. *IEEE Access* **2023**, *11*, 77163–77227. [CrossRef]
28. Embarak, O. An Adaptive Paradigm for Smart Education Systems in Smart Cities using the Internet of Behaviour (IoB) and Explainable Artificial Intelligence (XAI). In Proceedings of the 2022 8th International Conference on Information Technology Trends (ITT), Dubai, United Arab Emirates, 25–26 May 2022; pp. 74–79. [CrossRef]
29. Cheung, S.K.S.; Kwok, L.F.; Phusavat, K.; Yang, H.H. Shaping the Future Learning Environments with Smart Elements: Challenges and Opportunities. *Int. J. Educ. Technol. High. Educ.* **2021**, *18*, 16. [CrossRef] [PubMed]
30. Burlacu, M.; Boboc, R.G.; Butilă, E.V. Smart Cities and Transportation: Reviewing the Scientific Character of the Theories. *Sustainability* **2022**, *14*, 8109. [CrossRef]
31. Iyer, L.S. AI Enabled Applications Towards Intelligent Transportation. *Transp. Eng.* **2021**, *5*, 100083. [CrossRef]
32. Rocha, N.P.; Dias, A.; Santinha, G.; Rodrigues, M.; Queirós, A.; Rodrigues, C. Smart Cities and Public Health: A Systematic Review. *Procedia Comput. Sci.* **2019**, *164*, 516–523. [CrossRef]
33. Wielicka-Gańczarczyk, K.; Jonek-Kowalska, I. Involvement of Local Authorities in the Protection of Residents' Health in the Light of the Smart City Concept on the Example of Polish Cities. *Smart Cities* **2023**, *6*, 744–763. [CrossRef]
34. Ruiz-Vanoye, J.A.; Barrera-Cámara, R.A.; Díaz-Parra, O.; Ramos-Fernández, J.C.; Fuentes-Penna, A.; Ochoa-Zezzatti, A.; Hernández-Aguilar, J.A.; Campero-Jurado, I. Surveying Smart Farming for Smart Cities. In *AI, Edge and IoT-Based Smart Agriculture*; Academic Press: Cambridge, MA, USA, 2022; pp. 241–262.
35. Vermesan, O.; Friess, P. (Eds.) *Digitising the Industry Internet of Things Connecting the Physical, Digital and Virtual Worlds*; CRC Press: Boca Raton, FL, USA, 2022.
36. Wolfert, S.; Ge, L.; Verdouw, C.; Bogaardt, M.J. Big Data in Smart Farming—A Review. *Agric. Syst.* **2017**, *153*, 69–80. [CrossRef]
37. Bacco, M.; Barsocchi, P.; Ferro, E.; Gotta, A.; Ruggeri, M. The Digitisation of Agriculture: A Survey of Research Activities on Smart Farming. *Array* **2019**, *3*, 100009. [CrossRef]
38. Moustaka, V.; Theodosiou, Z.; Vakali, A.; Kounoudes, A.; Anthopoulos, L.G. Enhancing Social Networking in Smart Cities: Privacy and Security Borderlines. *Technol. Forecast. Soc. Chang.* **2019**, *142*, 285–300. [CrossRef]

39. Bianchini, D.; Avila, I. Smart Cities and Their Smart Decisions: Ethical Considerations. *IEEE Technol. Soc. Mag.* **2014**, *33*, 33–40. [CrossRef]
40. Efstathiades, H.; Antoniades, D.; Pallis, G.; Dikaiakos, M.-D. Identification of Key Locations Based on Online Social Network Activity. In Proceedings of the IEEE/ACM International Conference on Advances in Social Networks Analysis and Mining, Paris, France, 25–28 August 2015. [CrossRef]
41. Doran, D.; Severin, K.; Gokhale, S.; Dagnino, A. Social Media Enabled Human Sensing for Smart Cities. *AI Commun.* **2016**, *29*, 57–75. Available online: http://knoesis.wright.edu/sites/default/files/aic14.pdf (accessed on 28 December 2017). [CrossRef]
42. Osterrieder, P.; Budde, L.; Friedli, T. The Smart Factory as a Key Construct of Industry 4.0: A Systematic Literature Review. *Int. J. Prod. Econ.* **2020**, *221*, 107476. [CrossRef]
43. Lasi, H.; Fettke, P.; Kemper, H.G.; Feld, T.; Hoffmann, M. Industry 4.0. *Bus. Inf. Syst. Eng.* **2014**, *6*, 239–242. [CrossRef]
44. Silva, B.N.; Khan, M.; Han, K. Towards Sustainable Smart Cities: A Review of Trends, Architectures, Components, and Open Challenges in Smart Cities. *Sustain. Cities Soc.* **2018**, *38*, 697–713. [CrossRef]
45. Jabbar, H. The Visible Hand: Markets, Politics, and Regulation in Post-Katrina New Orleans. *Harv. Educ. Rev.* **2016**, *86*, 1–26. [CrossRef]
46. Salleh, M.S.M.; Fahmy-Abdullah, M.; Sufahani, S.F.; Bin Ali, M.K. Smart Cities with Smart Environment. In *Proceedings of the Third International Conference on Trends in Computational and Cognitive Engineering, Parit Raja, Malaysia, 21–22 October 2022*; Lecture Notes in Networks and Systems; Springer: Singapore, 2022; Volume 348. [CrossRef]
47. Aletà, N.B.; Alonso, C.M.; Ruiz, R.M.A. Smart Mobility and Smart Environment in the Spanish Cities. *Transp. Res. Procedia* **2017**, *24*, 163–170. [CrossRef]
48. Stone, M.; Knapper, J.; Evans, G.; Aravopoulou, E. Information Management in the Smart City. *Bottom Line* **2018**, *31*, 234–249. [CrossRef]
49. Owa, F.D. Water Pollution: Sources, Effects, Control and Management. *Mediterr. J. Soc. Sci.* **2013**, *4*, 65–68. [CrossRef]
50. Jha, A.V.; Appasani, B.; Ghazali, A.N.; Luqman, A.; Rajahputra, N.Z. Smart Grid Cyber-Physical Systems: Communication Technologies, Standards and Challenges. *Wirel. Netw.* **2021**, *27*, 2595–2613. [CrossRef]
51. Available online: https://www.youtube.com/watch?v=X2i7EBRmkaY (accessed on 3 July 2023).
52. Chehri, A.; Jeon, G.; Fofana, I.; Imran, A.; Saadane, R. Accelerating Power Grid Monitoring with Flying Robots and Artificial Intelligence. *IEEE Commun. Stand. Mag.* **2021**, *5*, 48–54. [CrossRef]
53. Stuhne, D.; Hoang, V.D.; Vasiljevic, G.; Bogdan, S.; Kovacic, Z.; Ollero, A.; Ebeid, E.S.M. Design of a Wireless Drone Recharging Station and a Special Robot End Effector for Installation on a Power Line. *IEEE Access* **2022**, *10*, 88719–88737. [CrossRef]
54. Fang, X.; Misra, S.; Xue, G.; Yang, D. Smart grid—The new and improved power grid: A survey. *IEEE Commun. Surv. Tutor.* **2012**, *14*, 944–980. [CrossRef]
55. Von Dollen, D. Report to NIST on the Smart Grid Interoperability Standards Roadmap. Electric Power Research Institute (EPRI) and National Institute of Standards and Technology. 2009. Available online: https://www.energy.gov/sites/prod/files/oeprod/DocumentsandMedia/Report_to_NIST_August10_2.pdf (accessed on 3 October 2023).
56. Alharthi, S.; Johnson, P.; Alharthi, M.; Jose, C. IoT/CPS Ecosystem for Efficient Electricity Consumption: Invited Paper. In Proceedings of the 2019 Tenth International Green and Sustainable Computing Conference (IGSC), Alexandria, VA, USA, 21–24 October 24 2019; pp. 1–7. [CrossRef]
57. Paul, S.; Rabbani, M.S.; Kundu, R.K.; Zaman, S.M.R. A review of smart technology (Smart Grid) and its features. In Proceedings of the 2014 1st International Conference on Non Conventional Energy (ICONCE 2014), Kalyani, India, 16–17 January 2014; pp. 200–203. [CrossRef]
58. Isern, J.; Jimenez-Perera, G.; Medina-Valdes, L.; Chaves, P.; Pampliega, D.; Ramos, F.; Barranco, F. A Cyber-Physical System for Integrated Remote Control and Protection of Smart grid Critical Infrastructures. *J. Sign Process. Syst.* **2023**, *95*, 1127–1140 . [CrossRef]
59. IMT traffic estimates for the years 2020 to 2030, Jul. 2015. Available online: https://www.itu.int/pub/R-REP-M.2370-2015 (accessed on 3 October 2023).
60. Sharma, P.; Liu, H.; Wang, H.; Zhang, S. Securing wireless communications of connected vehicles with artificial intelligence. In Proceedings of the 2017 IEEE International Symposium on Technologies for Homeland Security, Waltham, MA, USA, 25–26 April 2017; pp. 1–7.
61. Nawaz, S.J.; Sharma, S.K.; Wyne, S.; Patwary, M.N.; Asaduzzaman, M. Quantum machine learning for 6G communication networks: State-of-the-art and vision for the future. *IEEE Access* **2019**, *7*, 46317–46350. [CrossRef]
62. Tariq, M.; Ali, M.; Naeem, F.; Poor, H.V. Vulnerability Assessment of 6G-Enabled Smart Grid Cyber–Physical Systems. *IEEE Internet Things J.* **2021**, *8*, 5468–5475. [CrossRef]
63. Ahammed, T.B.; Patgiri, R.; Nayak, S. A vision on the artificial intelligence for 6G communication. *ICT Express* **2023**, *9*, 197–210. [CrossRef]
64. Mao, B.; Tang, F.; Kawamoto, Y.; Kato, N. Artificial-intelligence-enabled intelligent 6G networks. *IEEE Commun. Surv. Tutor.* **2021**, *24*, 210–247. [CrossRef]
65. Niu, Z.; Zhou, S.; Crespi, N. Greening 6G. In *Shaping Future 6G Networks*; Bertin, E., Crespi, N., Magedanz, T., Eds.; Wiley: New York, NY, USA, 2021. [CrossRef]
66. Hajam, S.S.; Sofi, S.A. IoT-Fog architectures in smart city applications: A survey. *China Commun.* **2021**, *18*, 117–140. [CrossRef]

67. Joudaki, M.; Zadeh, P.T.; Olfati, H.R.; Deris, S. A Survey on Deep Learning Methods for Security and Privacy in Smart Grid. In Proceedings of the 2020 15th International Conference on Protection and Automation of Power Systems (IPAPS), Shiraz, Iran, 30–31 December 2020; pp. 153–159. [CrossRef]
68. Gajanan, L.S.; Kirar, M.; Raju, M. Cyber-Attacks on Smart Grid System: A Review. In Proceedings of the 2022 IEEE 10th Power India International Conference (PIICON), New Delhi, India, 25–27 November 2022; IEEE: Piscataway, NJ, USA, 2022; pp. 1–6.
69. Ho, T.M.; Tran, T.D.; Nguyen, T.T.; Kazmi, S.; Le, L.B.; Hong, C.S.; Hanzo, L. Next-generation wireless solutions for the smart factory, smart vehicles, the smart grid and smart cities. *arXiv* **2019**, arXiv:1907.10102.
70. Khare, U.; Malviya, A.; Gawre, S.K.; Arya, A. Cyber Physical Security of a Smart Grid: A Review. In Proceedings of the 2023 IEEE International Students' Conference on Electrical, Electronics and Computer Science (SCEECS), Bhopal, India, 18–19 February 2023; pp. 1–6.
71. Zhao, Y.; Zhai, W.; Zhao, J.; Zhang, T.; Sun, S.; Niyato, D.; Lam, K.Y. A comprehensive survey of 6G wireless communications. *arXiv* **2020**, arXiv:2101.03889.
72. Braud, T.; Chatzopoulos, D.; Hui, P. Machine Type Communications in 6G. In *6G Mobile Wireless Networks*; Wu, Y., Ed.; Springer: Berlin/Heidelberg, Germany, 2021; pp. 153–167._11. [CrossRef]
73. Saad, W.; Bennis, M.; Chen, M. A vision of 6G wireless systems: Applications, trends, technologies, and open research problems. *IEEE Netw.* **2020**, *34*, 134–142. [CrossRef]
74. Tariq, F.; Khandaker, M.; Wong, K.K.; Imran, M.; Bennis, M.; Debbah, M. A speculative study on 6G. *arXiv* **2019**, arXiv:1902.06700.
75. Nayak, S.; Patgiri, R. 6G communication technology: A vision on intelligent healthcare. In *Health Informatics: A Computational Perspective in Healthcare*; Springer: Berlin/Heidelberg, Germany, 2021; pp. 1–18
76. Manogaran, G.; Rawal, B.S.; Saravanan, V.; Kumar, P.M.; Martínez, O.S.; Crespo, R.G.; Montenegro-Marin, C.E.; Krishnamoorthy, S. Blockchain based integrated security measure for reliable service delegation in 6G communication environment. *Comput. Commun.* **2020**, *161*, 248–256. [CrossRef]
77. Hewa, T.; Gur, G.; Kalla, A.; Ylianttila, M.; Bracken, A.; Liyanage, M. The role of blockchain in 6G: Challenges opportunities and research directions. In Proceedings of the 2nd 6G Wireless Summit (6G SUMMIT), Porto, Portugal, 17–20 March 2020; pp. 1–5.
78. Tomkos, I.; Klonidis, D.; Pikasis, E.; Theodoridis, S. Toward the 6G network era: Opportunities and challenges. *IT Prof.* **2020**, *22*, 34–38. [CrossRef]
79. Gao, H.; Su, Y.; Zhang, S.; Diao, M. Antenna selection and power allocation design for 5G massive MIMO uplink networks. *China Commun.* **2019**, *16*, 1–15.
80. Attarifar, M.; Abbasfar, A.; Lozano, A. Modified conjugate beam-forming for cell-free massive MIMO. *IEEE Wirel. Commun. Lett.* **2019**, *8*, 616–619. [CrossRef]
81. Vlachos, E.; Thompson, J. Energy-Efficiency Maximization of Hybrid Massive MIMO Precoding with Random-Resolution DACs via RF Selection. *IEEE Trans. Wirel. Commun.* **2021**, *20*, 1093–1104. [CrossRef]
82. Ghafoor, U.; Ali, M.; Khan, H.Z.; Siddiqui, A.M.; Naeem, M. NOMA and future 5G & B5G wireless networks: A paradigm. *J. Netw. Comput. Appl.* **2022**, *204*, 103413. [CrossRef]
83. Amin, A.A.; Shin, S.Y. Channel Capacity Analysis of Non-Orthogonal Multiple Access with OAM-MIMO System. *IEEE Wirel. Commun. Lett.* **2020**, *9*, 1481–1485. [CrossRef]
84. Al Amin, A.; Shin, S.Y. Capacity Enhancement of NOMA-MIMO with OAM-IM. *IEEE Wirel. Commun. Lett.* **2021**, *10*, 924–928. [CrossRef]
85. Al Amin, A.; Shin, S.Y. Capacity Analysis of Cooperative NOMA-OAM-MIMO Based Full-Duplex Relaying for 6G. *IEEE Wirel. Commun. Lett.* **2021**, *10*, 1395–1399. [CrossRef]
86. Al Amin, A.; Shin, S.Y. Investigate the Dominating Factor of Hybrid SWIPT Protocol by Performance Analysis of the Far User of Hybrid SWIPT based CNOMA Downlink Transmission. In Proceedings of the 2019 International Conference on Electrical, Computer and Communication Engineering (ECCE), Cox'sBazar, Bangladesh, 7–9 February 2019; pp. 1–6. [CrossRef]
87. Al Amin, A.; Shin, S.Y. Performance analysis of cooperative nonorthogonal multiple access with improved time switching simultaneous wireless information and power transfer protocol. *Trans. Emerg. Telecommun. Technol.* **2020**, *31*, e4433. [CrossRef]
88. Al Amin, A.; Shin, S.Y. Performance evaluation of cooperative-nonorthogonal multiple access-based improved hybrid simultaneous wireless information and power transfer protocol. *Trans. Emerg. Telecommun. Technol.* **2023**, *34*, e4662. [CrossRef]
89. Kader, M.F.; Uddin, M.B.; Islam, A.; Shin, S.Y. Cooperative non-orthogonal multiple access with SWIPT over Nakagami-m fading channels. *Trans. Emerg. Telecommun. Technol.* **2019**, *30*, e3571. [CrossRef]
90. Uddin, M.B.; Kader, M.F.; Shin, S.Y. Exploiting NOMA in D2D assisted full-duplex cooperative relaying. *Phys. Commun.* **2020**, *38*, 100914. [CrossRef]
91. Aswathi, V.; Babu, A.V. Full/half duplex cooperative relaying NOMA network under power splitting based SWIPT: Performance analysis and optimization. *Phys. Commun.* **2021**, *46*, 101335.
92. Adila, A.S.; Husam, A.; Husi, G. Towards the self-powered Internet of Things (IoT) by energy harvesting: Trends and technologies for green IoT. In Proceedings of the 2018 2nd International Symposium on Small-scale Intelligent Manufacturing Systems (SIMS), Cavan, Ireland, 16–18 April 2018; pp. 1–5. [CrossRef]
93. Hawasli, M.; Çolak, S.A. Toward green 5G heterogeneous small-cell networks: Power optimization using load balancing technique. *AEU-Int. J. Electron. Commun.* **2017**, *82*, 474–485. [CrossRef]

94. Zhang, H.; Feng, M.; Long, K.; Karagiannidis, G.K.; Nallanathan, A. Artificial Intelligence-Based Resource Allocation in Ultradense Networks: Applying Event-Triggered Q-Learning Algorithms. *IEEE Veh. Technol. Mag.* **2019**, *14*, 56–63. [CrossRef]
95. Björnson, E.; Özdogan, Ö.; Larsson, E.G. Reconfigurable Intelligent Surfaces: Three Myths and Two Critical Questions. *IEEE Commun. Mag.* **2020**, *58*, 90–96. [CrossRef]
96. Chen, J.C. Capacity improvement for intelligent reflecting surface-assisted wireless systems with a small portion of active elements. *IEEE Access* **2022**, *10*, 100438–100445. [CrossRef]
97. Lin, T.; Zhu, Y. Beamforming Design for Large-Scale Antenna Arrays Using Deep Learning. *IEEE Wirel. Commun. Lett.* **2020**, *9*, 103–107. [CrossRef]
98. Wang, M.; Zhu, T.; Zhang, T.; Zhang, J.; Yu, S.; Zhou, W. Security and Privacy in 6G Networks: New Areas and New Challenges. *Digit. Commun. Netw.* **2020**, *6*, 281–291. [CrossRef]
99. Islam, A.; Al Amin, A.; Shin, S.Y. FBI: A Federated Learning-Based Blockchain-Embedded Data Accumulation Scheme Using Drones for Internet of Things. *IEEE Wirel. Commun. Lett.* **2022**, *11*, 972–976. [CrossRef]
100. Nguyen, V.L.; Lin, P.C.; Cheng, B.C.; Hwang, R.H.; Lin, Y.D. Security and privacy for 6G: A survey on prospective technologies and challenges. *IEEE Commun. Surv. Tutor.* **2021**, *23*, 2384–2428. [CrossRef]
101. Kar, U.N.; Sanyal, D.K. An overview of device-to-device communication in cellular networks. *ICT Express* **2018**, *4*, 203–208. [CrossRef]
102. Abrahamsen, F.E.; Ai, Y.; Cheffena, M. Communication technologies for smart grid: A comprehensive survey. *Sensors* **2021**, *21*, 8087. [CrossRef] [PubMed]
103. Huang, Y.; Sun, Q.; Li, Y.; Sun, C.; Chen, Z. Damping technique empowered robust energy flow calculation for integrated energy systems. *Appl. Energy* **2023**, *343*, 121168. [CrossRef]
104. Jayachandran, M.; Kalaiarasy, C. Power-domain NOMA for massive connectivity in smart grid communication networks. In *Proceedings of the International Conference on Power Electronics and Renewable Energy Systems: ICPERES 2021, Chennai, India, 25 March 2021*; Springer: Singapore, 2022; pp. 205–212.
105. Ding, Z.; Fan, P.; Poor, H.V. Impact of user pairing on 5G nonorthogonal multiple-access downlink transmissions. *IEEE Trans. Veh. Technol.* **2016**, *65*, 6010–6023. [CrossRef]
106. Bhatia, V.; Swami, P.; Sharma, S.; Mitra, R. Non-orthogonal multiple access as an enabler for massive connectivity for 5G and beyond networks. *arXiv* **2019**, arXiv:1912.07077.
107. Qin, Z.; Yue, X.; Liu, Y.; Ding, Z.; Nallanathan, A. User Association and Resource Allocation in Unified NOMA Enabled Heterogeneous Ultra Dense Networks. *IEEE Commun. Mag.* **2018**, *56*, 86–92. [CrossRef]
108. Yang, B.; Katsaros, K.V.; Chai, W.K.; Pavlou, G. Cost-efficient low latency communication infrastructure for synchrophasor applications in smart grids. *IEEE Syst. J.* **2016**, *12*, 948–958. [CrossRef]
109. Katsaros, K.V.; Yang, B.; Chai, W.K.; Pavlou, G. Low latency communication infrastructure for synchrophasor applications in distribution networks. In Proceedings of the 2014 IEEE International Conference on Smart Grid Communications (SmartGridComm), Venice, Italy, 3–6 November 2014; pp. 392–397. [CrossRef]
110. Xenofontos, C.; Zografopoulos, I.; Konstantinou, C.; Jolfaei, A.; Khan, M.K.; Choo, K.K.R. Consumer commercial and industrial iot (in) security: Attack taxonomy and case studies. *IEEE Internet Things J.* **2021**, *9*, 199–221. [CrossRef]
111. Hossain, M.T.; Islam, S.; Badsha, S.; Shen, H. Desmp: Differential privacy-exploited stealthy model poisoning attacks in federated learning. *arXiv* **2021**, arXiv:2109.11141.
112. Hossain, M.T.; Badsha, S.; Shen, H. Privacy security and utility analysis of differentially private cpes data. *arXiv* **2021**, arXiv:2106.11225.
113. Zografopoulos, I.; Konstantinou, C. Detection of malicious attacks in autonomous cyber-physical inverter-based microgrids. *IEEE Trans. Ind. Inform.* **2021**, *18*, 5815–5826. [CrossRef]
114. Liu, T.; Tan, Z.; Xu, C.; Chen, H.; Li, Z. Study on deep reinforcement learning techniques for building energy consumption forecasting. *Energy Build.* **2020**, *208*, 109675. [CrossRef]
115. Islam, S.; Zografopoulos, I.; Hossain, M.T.; Badsha, S.; Konstantinou, C. A Resource Allocation Scheme for Energy Demand Management in 6G-enabled Smart Grid. In Proceedings of the 2023 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT), Washington, DC, USA, 16–19 January 2023; pp. 1–5. [CrossRef]
116. Bouzinis, P.S.; Diamantoulakis, P.D.; Karagiannidis, G.K. Wireless Federated Learning (WFL) for 6G Networks Part I: Research Challenges and Future Trends. *IEEE Commun. Lett.* **2022**, *26*, 3–7. [CrossRef]
117. Su, Z.; Tan, C.L.; Kong, Y.; Nallanathan, A. Secure and Efficient Federated Learning for Smart Grid with Edge-Cloud Collaboration. *IEEE Trans. Ind. Inform.* **2022**, *18*, 1333–1344. [CrossRef]
118. Borenius, S.; Hämmäinen, H.; Lehtonen, M.; Ahokangas, P. Smart grid evolution and mobile communications—Scenarios on the Finnish power grid. *Electr. Power Syst. Res.* **2021**, *199*, 107367. [CrossRef]
119. Albogamy, F.R.; Khan, S.A.; Hafeez, G.; Murawwat, S.; Khan, S.; Haider, S.I.; Basit, A.; Thoben, K.-D. Real-Time Energy Management and Load Scheduling with Renewable Energy Integration in Smart Grid. *Sustainability* **2022**, *14*, 1792. [CrossRef]
120. Guddanti, K.P.; Matavalam, A.R.R.; Weng, Y. PMU-Based Distributed Non-Iterative Algorithm for Real-Time Voltage Stability Monitoring. *IEEE Trans. Smart Grid* **2020**, *11*, 5203–5215. [CrossRef]

121. US-Canada Power System Outage Task Force. Final Report on the August 14 2003 Blackout in the United States and Canada. 2004. Available online: https://cybercemetery.unt.edu/archive/energyreport/20090701154100/https://reports.energy.gov/ (accessed on 3 October 2023)
122. Zhao, Y.; Chen, J.; Poor, H.V. A Learning-to-Infer Method for Real-Time Power Grid Multi-Line Outage Identification. *IEEE Trans. Smart Grid* **2020**, *11*, 555–564. [CrossRef]
123. Shukla, A.; Dutta, S.; Sadhu, P.K. An island detection approach by μ-PMU with reduced chances of cyber attack. *Int. J. Electr. Power Energy Syst.* **2021**, *126*, 106599. [CrossRef]
124. Serghiou, D.; Khalily, M.; Brown, T.W.C.; Tafazolli, R. Terahertz Channel Propagation Phenomena, Measurement Techniques and Modeling for 6G Wireless Communication Applications: A Survey, Open Challenges and Future Research Directions. *IEEE Commun. Surv. Tutor.* **2022**, *24*, 1957–1996. [CrossRef]
125. Kokkoniemi, J.; Rintanen, P.; Lehtomaki, J.; Juntti, M. Diffraction effects in terahertz band—Measurements and analysis. In Proceedings of the IEEE Global Communications Conference (GLOBECOM), Washington, DC, USA, 4–8 December 2016; pp. 1–6. [CrossRef]
126. Gandotra, P.; Jha, R.K.; Jain, S. Green Communication in Next Generation Cellular Networks: A Survey. *IEEE Access* **2017**, *5*, 11727–11758. [CrossRef]
127. Mwashita, W.; Odhiambo, M.O. Base station energy efficiency improvement for next generation mobile networks. *Int. J. Electron. Telecommun.* **2017**, *63*, 187–194. [CrossRef]
128. Alamu, O.; Gbenga-Ilori, A.; Adelabu, M.; Imoize, A.; Ladipo, O. Energy efficiency techniques in ultra-dense wireless heterogeneous networks: An overview and outlook. *Eng. Sci. Technol. Int. J.* **2020**, *23*, 1308–1326. [CrossRef]
129. Chergui, H.; Ksentini, A.; Blanco, L.; Verikoukis, C. Toward Zero-Touch Management and Orchestration of Massive Deployment of Network Slices in 6G. *IEEE Wirel. Commun.* **2022**, *29*, 86–93. [CrossRef]
130. Zhang, S.; Zhang, H.; Song, L. Beyond D2D: Full Dimension UAV-to-Everything Communications in 6G. *IEEE Trans. Veh. Technol.* **2020**, *69*, 6592–6602. [CrossRef]
131. Lombardi, R. Wireless backhaul for IMT 2020/5G: Overview and introduction. In Proceedings of the Workshop on Evolution of Fixed Service in Backhaul Support of IMT 2020/5G, Geneva, Switzerland, 29 April 2019.
132. Lee, S.-H.; Al Amin, A.; Shin, S.-Y. Orbital Angular Momentum-Based Multiple-Input-Multiple-Output with Receive Antenna Shift Keying for 6G. *Electronics* **2021**, *10*, 1567. [CrossRef]
133. Shaddad, R.Q.; Saif, E.M.; Saif, H.M.; Mohammed, Z.Y.; Farhan, A.H. Channel Estimation for Intelligent Reflecting Surface in 6G Wireless Network via Deep Learning Technique. In Proceedings of the 2021 1st International Conference on Emerging Smart Technologies and Applications (eSmarTA), Sana'a, Yemen, 10–12 August 2021; pp. 1–5. [CrossRef]
134. Mucchi, L.; Giannetti, F.; Foschini, G.J.; Chiani, M. Physical-Layer Security in 6G Networks. *IEEE Open J. Commun. Soc.* **2021**, *2*, 1901–1914. [CrossRef]
135. Ahmad, I.; Shahabuddin, S.; Kumar, T.; Okwuibe, J.; Gurtov, A.; Ylianttila, M. Security for 5G and Beyond. *IEEE Commun. Surv. Tutor.* **2019**, *21*, 3682–3722. [CrossRef]
136. Mohsan, S.A.H.; Li, Y.; Shvetsov, A.V.; Varela-Aldás, J.; Mostafa, S.M.; Elfikky, A. A Survey of Deep Learning Based NOMA: State of the Art, Key Aspects, Open Challenges and Future Trends. *Sensors* **2023**, *23*, 2946. [CrossRef]