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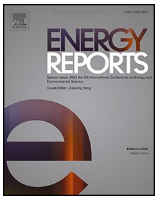

Research paper

Unleashing the potential of sixth generation (6G) wireless networks in smart energy grid management: A comprehensive review

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ABSTRACT

As the world continues to seek sustainable and efficient energy solutions, the integration of advanced technologies into smart energy grid management (SEGM) becomes a paramount focus. The advent of Sixth Generation (6G) wireless networks promises to revolutionize the way energy grids are monitored, controlled, and optimized. This review paper explores the potential of 6G wireless networks in the context of SEGM. It discusses the vision and potential techniques that can be harnessed to unlock the full capabilities of 6G networks. The paper delves into the challenges and opportunities presented by 6G technology, addressing issues such as scalability, security, real-time monitoring, and dynamic spectrum access. Moreover, it explores how 6G wireless networks can enable seamless integration with other advanced technologies, such as blockchain and cybertwin, to enhance the resilience and reliability of smart energy grids. The comprehensive review aims to shed light on the transformative role of 6G wireless networks, paving the way for a sustainable and intelligent future in energy grid management.

1. Introduction

The traditional energy grid has long been the backbone of power distribution, relying on centralized generation and a unidirectional flow of electricity (Azmi et al., 2022). However, in recent years, the need for a more sustainable and resilient energy infrastructure has become increasingly apparent. Climate change concerns, the depletion of fossil fuel resources, and the growing demand for electricity have spurred the development of smarter and more efficient power distribution systems. Enter the concept of smart energy grids. These innovative grids integrate advanced technologies, communication systems, and intelligent management techniques to optimize energy generation, distribution, and consumption. Smart grids enable bidirectional flow of electricity, real-time monitoring, and sophisticated control mechanisms that enhance the overall efficiency, reliability, and sustainability of energy distribution (Alsharif, 2017a). The significance of smart energy grid management (SEGM) lies in its ability to address the limitations of traditional grids while meeting the evolving energy needs of society. By incorporating cutting-edge technologies, such as advanced metering infrastructure (AMI), distributed energy resources (DERs), demand response (DR) systems, grid automation, and energy management systems (EMS). Moreover, SEGM facilitates the seamless integration of renewable energy sources (RESs), such as solar and wind power, into the grid. This integration helps reduce reliance on fossil fuels and mitigate greenhouse gas emissions, aligning with global sustainability goals (Goudarzi et al., 2022). Additionally, smart grids improve the resilience of energy infrastructure by enabling real-time monitoring, fault detection, and self-healing capabilities, ensuring reliable power supply even in the face of disruptions (Abdullah and Hassan, 2022). Efficiency gains are another key advantage of SEGM. By optimizing energy distribution, minimizing transmission losses, and balancing loads, smart grids reduce wastage and enhance overall energy efficiency. Consumers also benefit from increased control over their energy consumption through real-time data access, energy-saving insights, and demand-response programs. This empowers consumers to make informed decisions and reduce their energy costs. Furthermore, SEGM supports grid flexibility and demand management. By incentivizing consumers to adjust their energy usage during peak demand periods, smart grids enable grid operators to balance supply and demand, avoid overloads, and defer costly

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Nomenclature

5G	Fifth Generation.
6G	Generation.
AI	Artificial Intelligence.
AMI	Advanced Metering Infrastructure.
AR	Augmented Reality.
BC	Blockchain.
BM	Biomass.
CAES	Compressed-Air Energy Storage.
CO_2	Carbon di oxide.
CSP	Concentrated Solar Power.
DERs	Distributed Energy Resources.
DG	Distributed Generation.
DR	Demand Response.
EMS	Energy Management System.
SEGM	Smart Energy Grid Management.
ESSs	Energy Storage Systems.
GE	Geothermal energy.
IoT	Internet of Things.
MG	Multi Generation.
MIMO	Multiple-Input and Multiple-Output.
ML	Machine Learning.
P2P	Peer-to-Peer.
PV	Photovoltaic.
RES	Renewable Energy Sources.
SMES	Superconducting magnetic energy storage.
THz	Terahertz.
URLLC	Ultra-Reliable and Low-Latency Communications.
VR	Virtual Reality.
WT	Wind Turbine.

infrastructure upgrades. This flexibility contributes to a more stable and efficient energy system (Alsharif, 2017b).

However, the widespread adoption and deployment of smart energy grids face several challenges that need to be addressed. One of these challenges is the underutilization of the vast amount of data generated by smart grids. Despite the availability of valuable data from sensors, meters, and control systems, effectively analyzing and harnessing this data to derive actionable insights and optimize grid operations remains a complex task (Judge et al., 2022). Another significant challenge is the sluggish connectivity between sensors and components within the grid. Timely and seamless exchange of information is crucial for efficient grid management. However, existing communication systems may suffer from slow connectivity, leading to delays in data transmission and hindering real-time responsiveness of the grid (Aggarwal et al., 2021). Regular maintenance requirements pose another obstacle in the widespread deployment of smart energy grids. With the complex network of sensors, meters, and other components involved, ensuring their proper functioning and reliability necessitates routine maintenance activities. These maintenance tasks can be resource-intensive and time-consuming, potentially impacting the overall efficiency and operation of the grid (Rae et al., 2020). Furthermore, the intermittent nature of RES such as solar and wind power presents a unique challenge in SEGM. The availability of RES is subject to fluctuations, dependent on weather conditions, which can pose challenges in integrating these intermittent energy sources into the grid and effectively balancing their generation with energy demand (Meenal et al., 2022; Basit et al., 2020). To address these challenges and unlock the full potential of smart energy grids, the emergence of the next-generation wireless communication standard known as 6G offers a promising solution. With its advanced capabilities and features, 6G has the potential to revolutionize grid communication and data exchange, enabling faster and more reliable connectivity between sensors and components (Alsharif et al., 2020). By leveraging 6G technology, smart energy grids can overcome the challenges of underutilized big data, sluggish connectivity, regular maintenance needs, and the intermittent nature of RES, paving the way for a more efficient, reliable, and sustainable energy future.

6G wireless networks offer several key advantages that can greatly support and enhance smart grid networks. One significant aspect is the significantly faster data transmission speeds provided by 6G. This allows for the quick and efficient exchange of large volumes of data between different components of the smart grid, including sensors, meters, substations, and control centers. Real-time data sharing is crucial for monitoring grid conditions, managing power generation and distribution, and optimizing energy usage (Alsharif et al., 2021). In addition to speed, 6G networks offer ultra-low latency, meaning there is minimal delay in data transmission. This real-time responsiveness is vital for time-critical applications within smart grids, such as grid fault detection, isolation, and recovery. With 6G, smart grid systems can detect and respond to issues in near real-time, improving the overall reliability and resilience of the grid (Goudarzi et al., 2022). Another advantage of 6G is its higher capacity compared to previous generations of wireless networks. This increased capacity allows for the connectivity of a larger number of devices and sensors in the smart grid ecosystem. It supports the vision of the Internet of Things (IoT) within the smart grid, enabling seamless communication among a vast array of devices, meters, and appliances. This interconnectedness enhances grid management and enables intelligent EMS to optimize energy usage and reduce waste (Goudarzi et al., 2022). Moreover, 6G networks offer improved reliability, ensuring that critical communication links remain stable and operational even in challenging conditions. This reliability is vital for the seamless integration of RESs, as intermittent power generation from sources like solar and wind must be effectively managed and balanced with energy demand. With 6G, smart grid systems can better forecast and manage fluctuations in renewable energy generation, resulting in a more stable and efficient grid (Yap et al., 2022). Furthermore, the integration of 6G with emerging technologies such as artificial intelligence (AI), edge computing, and blockchain (BC) holds significant promise for smart grid networks. AI algorithms can analyze massive amounts of data collected from smart grid devices and sensors, enabling predictive maintenance, energy optimization, and demand-response mechanisms. Edge computing brings computation closer to the devices, reducing latency and enabling real-time analytics and decision-making at the grid's edge. BC technology can enhance the security, transparency, and trustworthiness of smart grid transactions, ensuring the integrity of data and facilitating peer-to-peer (P2P) energy trading (Afzal et al., 2022).

In light of these advantages, exploring and understanding the principles, technologies, and potential of SEGM is essential for driving the transition towards a sustainable, reliable, and intelligent energy future. This paper aims to delve into the vision, potential, and future directions of leveraging 6G wireless networks to support SEGM. By examining the capabilities and applications of 6G, we can explore how it can revolutionize the management of energy grids, optimize renewable energy integration, enhance grid resilience, and unlock new possibilities for energy efficiency and demand management. The key contributions of this study are as follows:

- Provides a thorough analysis of SEGM, covering its background, significance, and key components. By exploring the challenges faced in the adoption and deployment of smart grids, including underutilization of big data, sluggish connectivity, maintenance needs, and

the intermittent nature of RESs, the study sets the stage for understanding the potential of 6G wireless networks as a solution.
- Focuses on the emerging 6G wireless communication standard and its potential in addressing the challenges of SEGM. It delves into the features, capabilities, and advancements offered by 6G, providing insights into how this technology can revolutionize grid communication and data exchange.
- Highlights the range of cutting-edge technologies that can be facilitated by 6G in the context of SEGM. These include augmented reality (AR)/virtual reality (VR) maintenance and troubleshooting, P2P energy trading, connected IoT, energy monitoring, EMS, industry 4.0, automation, cloud computing, and weather forecasting. By discussing these technologies, the study demonstrates the transformative potential of 6G in revolutionizing the RESs sector.
- Offers a forward-looking perspective on the vision and future directions of leveraging 6G wireless networks for SEGM. It discusses the potential benefits, such as enhanced renewable energy integration, improved grid resilience, efficient energy distribution, consumer empowerment, and grid flexibility. By highlighting these advantages, the study contributes to the understanding of how 6G can shape the future of smart energy grids and pave the way for a sustainable, reliable, and intelligent energy ecosystem.

This paper follows the subsequent structure: Section 2 presents the research methodology employed in the article, which outlines the sources of gather data, and analyze the findings. Section 3 provides a comprehensive overview of smart energy grids. It covers the fundamental concepts, components, and functionalities of these advanced grid systems. In Section 4, the paper addresses the key challenges and limitations faced by current grid management systems. It examines the issues that hinder the effective operation and management of energy grids and explores potential solutions to mitigate these challenges. Section 5 focuses on the vision and requirements of 6G wireless networks. It discusses the advancements expected in the next-generation wireless networks and how they can revolutionize communication and connectivity, especially in the context of SEGM. Section 6 delves into the various potential applications of 6G wireless networks specifically within the realm of SEGM. It explores how the unique capabilities of 6G networks can be leveraged to optimize energy distribution, grid monitoring, and overall grid efficiency. Lastly, Section 7 presents the conclusion of the paper.

2. Research methodology

To conduct this literature review on the potential of 6G wireless networks in SEGM, a systematic approach was employed to collect relevant information. The research questions (RQ) guiding the study were formulated using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method.

- ***RQ1:*** What is the smart energy grid? and What are the key challenges and limitations in the existing grid management systems?

  The primary focus of this question is twofold: firstly, to comprehend the concept of a smart energy grid, and secondly, to analyze the main challenges and limitations associated with existing grid management systems.
- ***RQ2:*** What are the potential 6G wireless network techniques that can be used to implement management for the smart energy grid?

  This question delves into the exploration of potential 6G wireless network techniques that can be leveraged to effectively implement management strategies for the smart energy grid. The objective is to assess the diverse techniques mentioned in the literature, evaluate their advantages, and identify current trends that can contribute to the successful implementation of SEGM.
- ***RQ3:*** What are the key challenges in designing and implementing a smart energy grid widely?

The central aim of this question is to thoroughly examine the critical challenges involved in designing and deploying a comprehensive smart energy grid. A comparative analysis will be performed between the limitations of existing grid management systems and the potential advantages offered by 6G wireless network techniques.

Once the research questions were identified, the research string (RS) was formulated by establishing the following keywords: "Smart grids", "Energy management systems", "Electrical grids", "6G", "IoT", "6G applications", "Renewable energy sources", and "Wireless networks".

Following the formulation of the research string (RS), the document search phase was initiated. This study consulted multiple databases, namely IEEE, Science Direct, Scopus, Web of Science, Springer, Wiley Online Library, MDPI database, and Association of Computing Machinery (ACM). The selection of these databases was based on their extensive coverage of publications and previous research in the field. An effort was made to include databases that have been utilized by other authors in previous studies. The number of articles retrieved from these databases proved to be sufficient, obviating the need for additional techniques to expand the results. The research process was structured into a three-stage approach, as depicted in Fig 1.

3. Overview of smart energy grids

Smart energy grids revolutionize energy distribution, diverging from traditional unidirectional flows by employing advanced technologies for optimized energy generation, distribution, and consumption (Abdullah and Hassan, 2022). Table 1 presents a brief comparison between smart energy grids and traditional grids.

The smart energy grids encompass three main components: generation, transmission, and power consumers (Abdullah and Hassan, 2022), as shown in Fig. 2.

3.1. Generation

Smart energy grids prioritize RESs like solar, wind, hydro, and biomass, alongside conventional sources (non-renewable) such as coal, gas, and nuclear power for electricity generation. Integration of RESs, particularly through DERs like solar photovoltaic (PV) and wind turbines (WTs), enhances sustainability and reduces emissions (Fan et al., 2021; Neffati et al., 2021).

3.1.1. Renewable energy integration

Fig. 3 illustrates the RESs in the current energy infrastructure aiming to mitigate carbon emissions, foster sustainability, and fortify energy security (Hoang and Nguyen, 2021). These sources include PV (Aquila et al., 2021), WTs (Darwish and Al-Dabbagh, 2020), thermal collectors (TCs) and photovoltaic thermal collectors (PV/T) (Khamlich et al., 2021), biomass (BM) (Zhang et al., 2020), geothermal energy (GE), and multi-generation (MG).

The variability and intermittency of RESs pose challenges in integrating them into existing energy infrastructure due to weather-induced fluctuations in solar and wind energy production. The smart energy grid is countering these challenges by adopting advanced technologies like Energy Storage Systems (ESSs) to store surplus energy and release it during peak demand. DR programs adjust consumption based on renewable energy availability. Microgrids offer localized energy systems, ensuring stable and reliable supply, and addressing RES variability for effective grid integration.

3.1.2. Energy storage systems (ESSs)

ESSs are pivotal in the smart grid as they store diverse energy forms like thermal, electrical, and kinetic energy (Zhang et al., 2019). ESS sources encompass batteries, supercapacitors (Mufti et al., 2009), superconducting magnetic energy storage (Ali et al., 2010), flywheels (Sebastián and Peña-Alzola, 2015), hydro-pumping (Sadi et al., 2023), thermal storage systems (Luján et al., 2022), and compressed-air energy

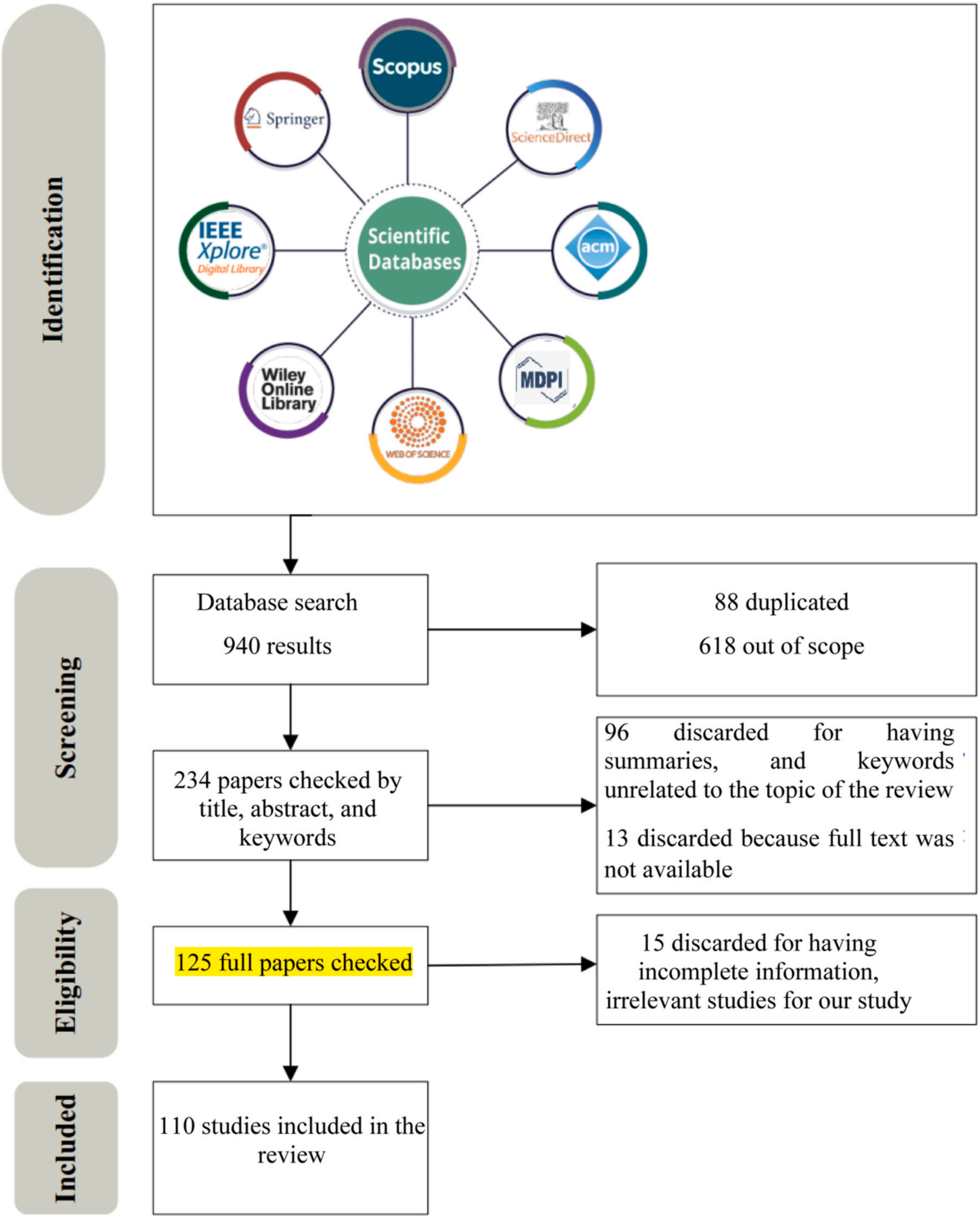

Fig 1. Research methodology of the article.

storage (Rabi et al., 2023), as illustrated in Fig. 4.

ESSs within smart grids present a spectrum of options with varying characteristics to accommodate distinct requirements, differing in power or storage capacity, response time, cost, and physical size (Tan et al., 2021). These variations allow for customization and optimization tailored to specific application needs. ESS applications fall into three primary categories based on discharge periods. First, Power Quality Storage systems swiftly deliver short-duration energy support to maintain stable power by managing voltage and frequency fluctuations. Second, Distributed Generation (DG) Storage systems store surplus energy from distributed RESs like solar panels or wind turbines, managing their intermittent generation and improving grid stability. Finally, Bulk Storage systems offer extended-duration energy storage for large-scale applications, storing excess energy during low demand periods and releasing it during peak demand, enabling efficient load management, and reducing reliance on conventional power plants.

3.2. *Transmission and distribution*

The transmission and distribution component focuses on the efficient and reliable delivery of electricity from generation sources to end-users. Smart energy grids utilize advanced technologies to optimize power

Table 1
Comparison between smart energy grids and traditional grids.

Aspect	Smart Energy Grids	Traditional Grids
Energy Source Diversity	Incorporates RES such as solar, wind, and hydro, reducing reliance on fossil fuels and promoting sustainability.	Primarily relies on fossil fuels (coal, oil, and gas) for energy generation, leading to higher carbon emissions and environmental impact.
Energy Efficiency	Utilizes advanced technologies for efficient energy production, distribution, and consumption, reducing energy losses and optimizing resource utilization.	Less emphasis on energy efficiency, resulting in higher energy losses and inefficient resource allocation.
Integration of Distributed Generation	Integrates DERs like rooftop solar PV and small WTs, enabling localized generation and reducing transmission losses.	Centralized power generation from large-scale power plants, requires extensive transmission infrastructure and results in higher transmission losses.
Grid Resilience and Flexibility	Incorporates grid automation, advanced control systems, and energy storage to enhance grid resilience, adaptability, and ability to handle intermittent RES.	Relies on conventional grid infrastructure with limited flexibility and adaptability, making it less resilient to disruptions and intermittent energy sources.
Real-time Monitoring and Control	Utilizes advanced sensors, communication networks, and data analytics for real-time monitoring, control, and optimization of grid operations, enhancing reliability and efficiency.	Relies on manual monitoring and control with limited real-time visibility into grid operations, leading to slower response times and less efficient operations.
Customer Engagement and Empowerment	Empowers consumers with energy usage information, DR programs, and smart devices for better energy management and cost savings.	Limited customer engagement and lack of tools to empower consumers for energy management, resulting in higher energy consumption and costs.
Environmental Impact	Significantly reduces greenhouse gas emissions and environmental impact by promoting clean energy generation and reducing reliance on fossil fuels.	Higher greenhouse gas emissions and environmental impact due to fossil fuel dependency and limited use of RES.

flow, reduce transmission losses, and enhance grid stability. These technologies include high-voltage transmission lines, smart substations, and grid automation systems. Additionally, smart energy grids employ sensors, communication networks, and intelligent control systems to monitor and manage the flow of electricity in real time. This enables operators to identify and address any disruptions or abnormalities promptly, ensuring a reliable and resilient grid infrastructure (Abdullah and Hassan, 2022; Hamidi et al., 2010).

3.3. Power consumers

Smart energy grids benefit both residential and commercial power consumers by providing real-time energy usage data, empowering informed decisions for energy-efficient practices. These grids support DR programs (Palensky and Dietrich, 2011), allowing users to adjust consumption, aid load balancing, and bolster grid stability. Incorporating energy storage technologies like batteries helps manage intermittent renewable energy generation, storing excess power for high-demand periods, and ensuring reliability. AMI facilitates communication between users and providers through smart meters, enabling accurate billing and dynamic energy consumption adjustments (Muratori et al., 2014). This interaction improves grid stability, optimizes usage, and avoids costly upgrades.

EMS provides advanced software tools and algorithms for optimizing energy generation, distribution, and consumption. It leverages data from various sources, including smart meters, sensors, and weather forecasts, to optimize energy flows, minimize losses, and improve overall grid efficiency (Kayastha et al., 2014). The key aspects of the EMS are:

- Real-time monitoring and data acquisition: EMS incorporates advanced sensing and metering devices, such as smart meters and sensors, to collect real-time data on energy consumption, generation, and grid conditions. These devices provide granular information about energy flows, load profiles, voltage levels, and other critical parameters. Real-time monitoring allows operators to have a comprehensive view of the grid's status, enabling them to identify issues, detect abnormalities, and respond promptly to any disturbances (Kayastha et al., 2014).
- Data analysis and visualization: EMS employs sophisticated data analytics techniques to process and analyze the vast amount of real-time data collected from the grid. Data analytics algorithms can detect patterns, anomalies, and trends in energy consumption and generation, enabling operators to gain valuable insights into grid performance. Visualizations and dashboards are used to present the analyzed data in a user-friendly manner, facilitating effective decision-making and providing stakeholders with clear visibility into the grid's operation and performance (Stefan et al., 2017).
- Load management and DR: EMS enables effective load management strategies by monitoring and controlling energy consumption in real-time. By analyzing historical data and considering factors such as peak demand periods and energy pricing, EMS can optimize energy usage and distribute loads efficiently. DR programs, facilitated by EMS, encourage consumers to adjust their energy consumption patterns in response to signals or incentives. This demand-side management helps balance supply and demand, reduces stress on the grid during peak periods, and minimizes the need for additional generation capacity (Law et al., 2012).
- Grid optimization and control: EMS incorporates advanced control algorithms to optimize the operation of the grid and ensure efficient utilization of energy resources. These algorithms consider factors such as load forecasts, energy generation capacity, and grid constraints to optimize power generation, distribution, and load balancing. EMS can automatically adjust settings, reroute power flows, and coordinate DERs to maximize grid efficiency and stability. Through precise control mechanisms, EMS helps prevent blackouts, reduce transmission losses, and optimize the utilization of RES (Roslan et al., 2019).
- Integration of DERs: Smart energy grids heavily rely on DERs, such as solar PV, WTs, and ESSs. EMS plays a crucial role in integrating and managing these distributed resources effectively. EMS coordinates the operation of DERs, ensuring their optimal utilization based on grid conditions, energy demand, and renewable energy availability. It facilitates seamless integration of DERs into the grid, enables bidirectional power flow, and ensures grid stability even in the presence of intermittent RES (Carr et al., 2008).
- Grid planning and expansion: EMS supports long-term grid planning and expansion by providing valuable insights into energy consumption patterns, load growth projections, and the impact of renewable energy integration. The data and analytics provided by EMS help grid operators make informed decisions regarding infrastructure upgrades, capacity additions, and the integration of new energy resources. This enables efficient and cost-effective grid expansion while ensuring the reliability and performance of the entire system (Jayachandran et al., 2022).

The next section delves into the importance of effective grid management, examining challenges associated with smart grids (such as grid flexibility, power quality, balancing, resilience, and optimizing

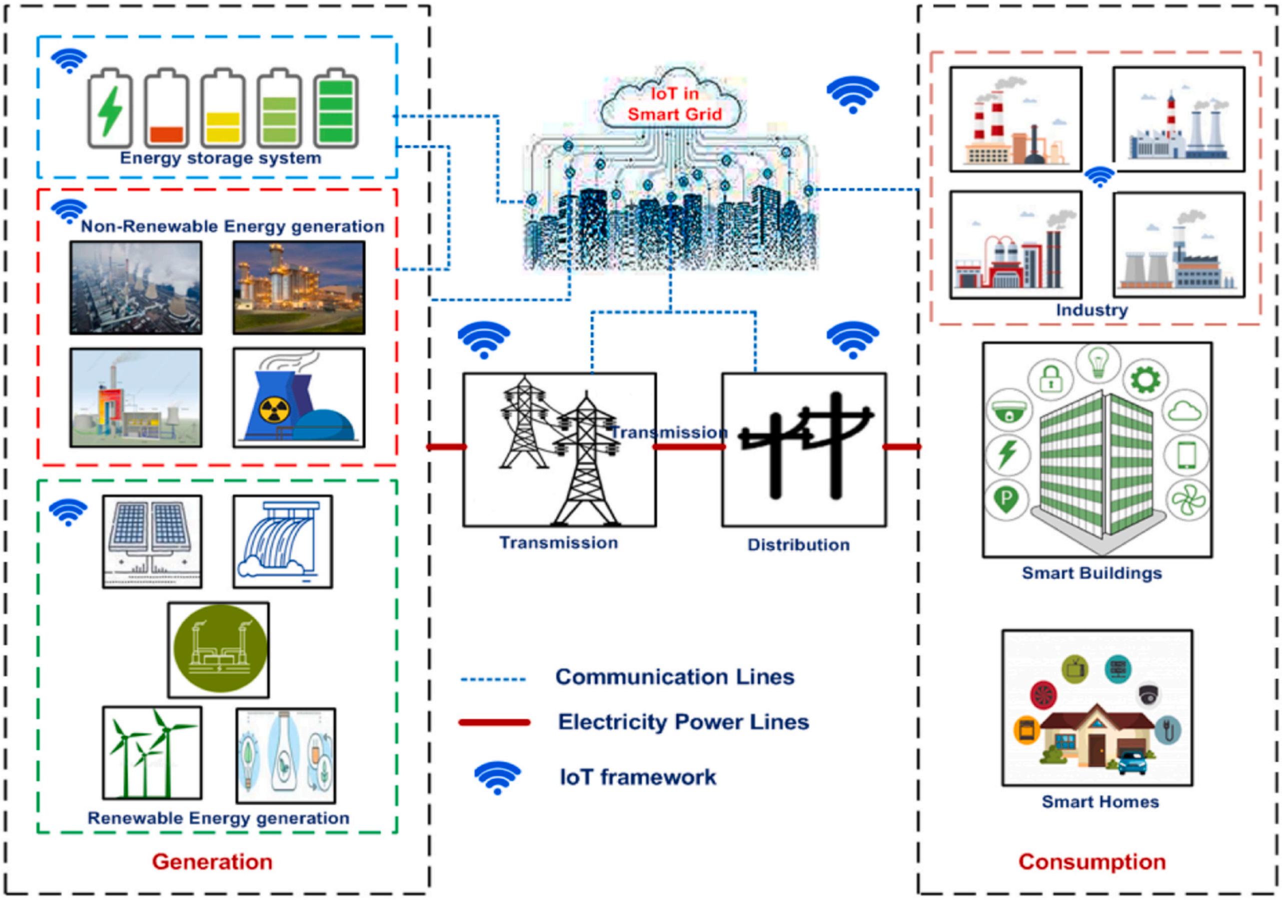

Fig. 2. The key components of a smart energy grid.

renewable energy utilization), alongside potential promising solutions.

4. Challenges and limitations in existing grid management systems

While existing grid management systems have made significant progress in supporting the integration of renewable energy, they still face certain challenges and limitations (Bari et al., 2014; Bhattarai et al., 2019). These challenges arise from the growing complexity of modern power grids and the increasing share of RES. Understanding and addressing these limitations is crucial for further enhancing grid management capabilities and ensuring the efficient integration of renewable energy.

- Limited Situational Awareness: Many traditional grid management systems lack real-time situational awareness, making it difficult for operators to monitor and respond to dynamic changes in the grid. This limitation hampers their ability to efficiently manage the variability and intermittency associated with renewable energy generation. As a result, grid operators often rely on conservative approaches that may lead to underutilization of renewable energy resources (Dahal et al., 2015; Dong et al., 2017).
- Inadequate Communication and Data Exchange: Effective grid management requires seamless communication and data exchange among various grid components, including generation sources, ESSs, and consumer devices. However, existing communication infrastructure and protocols may not be designed to handle the large volume of data generated by smart grids. This limitation can result in delays, data loss, and inefficient decision-making (Bari et al., 2014; Fan et al., 2012).
- Lack of Scalability and Flexibility: The increasing integration of distributed energy resources, such as rooftop solar panels and small-scale WTs, poses scalability and flexibility challenges for existing grid management systems. These systems were originally designed to handle centralized power generation and distribution, and may not be readily adaptable to the decentralized and dynamic nature of RES. As a result, the potential benefits of DERs may not be fully realized (Kim et al., 2010).
- Cybersecurity Risks: The digitization and increased connectivity of grid management systems also introduce cybersecurity risks. As smart grids rely on interconnected devices and communication networks, they become potential targets for cyberattacks. Protecting the grid infrastructure from cyber threats is essential to ensure the reliability and resilience of the energy system (Gunduz and Das, 2020; Wang et al., 2021).

To address these challenges and limitations, the next-generation wireless communication standard, 6G, emerges as a promising solution. 6G networks are expected to offer significant advancements in terms of speed, capacity, latency, and reliability (Alsharif et al., 2022). Table 2 summarizes the primary milestones in 6G compared to 5 G. The improvements in 6G will facilitate faster and more secure communication among grid components, enabling real-time monitoring, seamless data exchange, and prompt decision-making. With its potential to support massive machine-type communications, 6G can effectively handle the large volume of data generated by smart energy grids. This will enhance situational awareness, allowing grid operators to accurately monitor and manage the dynamic changes in renewable energy generation. Moreover, the ultra-reliable and low-latency communication capabilities of 6G networks will facilitate seamless coordination and

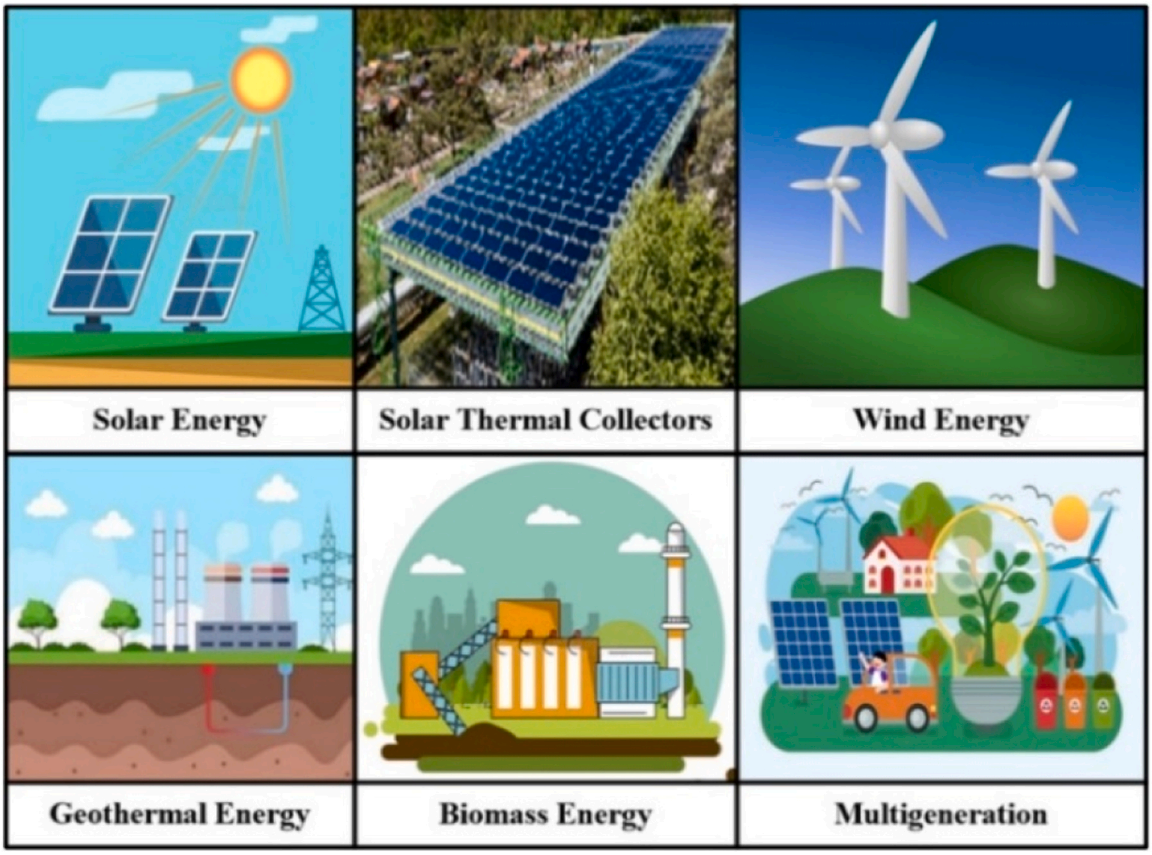

Fig. 3. A range of renewable energy resources.

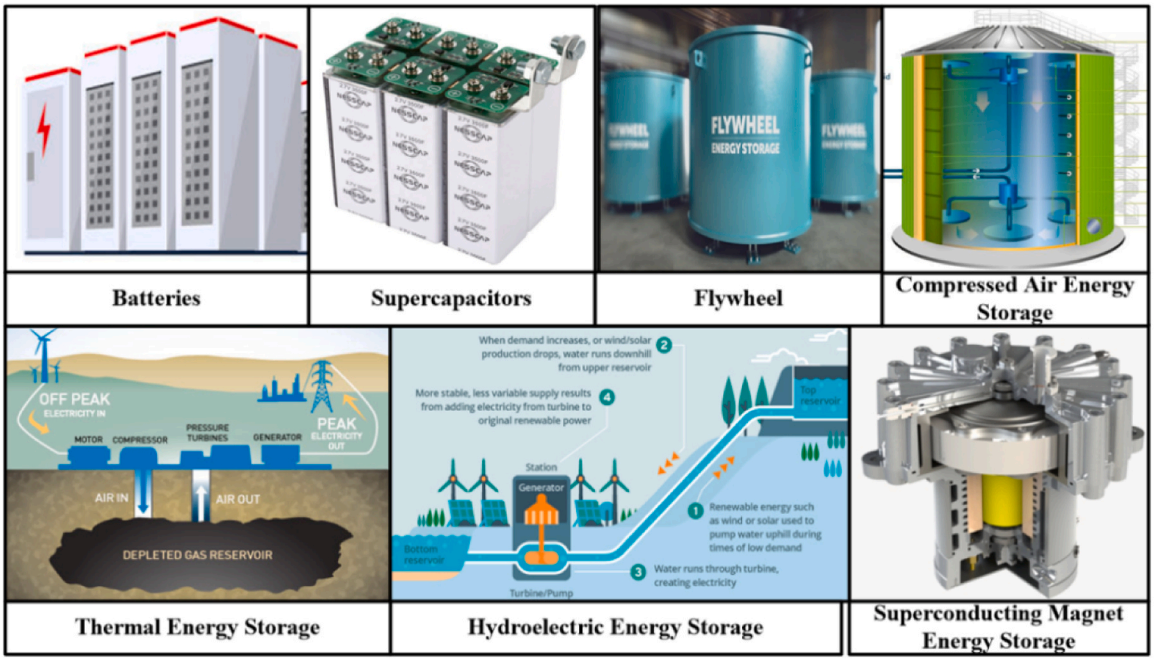

Fig. 4. Various ESSs.

control of distributed energy resources, enabling optimal grid balancing and utilization of RES. Additionally, the improved cybersecurity features of 6G networks will help mitigate risks and ensure the integrity and resilience of grid management systems. In the following sections, we will delve into the potential applications and benefits of 6G networks in SEGM, exploring how this next-generation technology can overcome the limitations of existing systems and drive the efficient integration of renewable energy.

Table 2
Key milestones of 6G compared to 5 G.

Aspect	5 G	6G
Spectrum	Sub-6 GHz and mmWave bands *Current:* Mid-Band (3.4 - 3.8 GHz) *Future:* High-Band (mmWave) (24 GHz, 28 GHz, 39 GHz, and 66 GHz)	Terahertz bands (95 GHz - 3 THz)
Data Rate	Up to multi-Gbps speeds *Peak:* 10 Gbps *Experience:* 1 Gbps	Up to Tera-bps speeds *Peak:* 1Tbps *Experience:* 100 Gbps
Latency	Around one millisecond or lower latency (>1 ms)	Ultra-low latency in the range of microseconds (100μs)
Connection Density	1 Million Devices/km^2	10 Million Devices/km^2
Spectrum Efficiency	3–5x relative to 4 G	3x relative to 5 G
Energy Efficiency	1000x relative to 4 G	10x relative to 5 G
Reliability	About 99.9%	> 99.999%
Network Slicing	Supports network slicing for customized services	Develop and refine network slicing capabilities
Security	Implements enhanced security protocols	More robust security measures, addressing potential vulnerabilities in network infrastructure
Support AI	Partial	Fully
Support AR, VR, ER	Partial	Fully
Satellite Integration	No	Fully
Use Cases	Supports enhanced mobile broadband, IoT, AR/VR	Intelligent connectivity, holographic communications, AI/ML, and immersive experiences

5. 6G wireless networks

As 5 G mobile communication technology is being deployed in various countries and its user base continues to grow, there is a need to shift focus toward the development of the next generation of communication systems, namely 6G. The implementation of 5 G is still ongoing globally, but it is crucial to prepare for the future demand of the information and communications technology sector by 2030 (Alsharif et al., 2022). Emerging applications like BC, AI, smart grids, and the IoT require substantial resources, extremely high data rates, and enhanced throughput ranging from gigabits per second to terabits per second. The evolution towards the next-generation cellular system is driven by the emergence of new applications, as well as the exponential growth of wireless traffic, with the aim of improving spectral efficiency, energy efficiency, and operational expenditures. The current capabilities of the 5 G network may not be sufficient to meet the requirements of modern applications such as AR/VR/ER, machine-to-machine communication, high-resolution video streaming, drone technologies, autonomous vehicles, holographic communication, and IoT-based applications. Therefore, the development of 6G networks becomes essential to fulfill the demands of the modern era (Alsharif et al., 2020).

While 5 G technology is still in its nascent stage, researchers and technology companies are already looking ahead to the next frontier: 6G. 6G is envisioned as the next generation of superhighway for data transmission, seamlessly connecting humans, sensors, autonomous vehicles, cloud resources, smart cities, and digital transactions to build an intelligent cyberphysical world. The advancements in 6G mobile communication technology aim to create an efficient wireless system that meets the current requirements of secure human communication, universal inclusion, self-intelligence, and disruptive services through the utilization of technologies like terahertz (THz), AI, machine learning (ML), and an expanded satellite constellation (Wang et al., 2023). The 6G network is expected to become the foundation of our daily lives, providing seamless global coverage, supporting industrial production, enabling secure and reliable connectivity without limitations, and fostering green development. This integration will accelerate the convergence of communication with sensing, control, and processing, making the 6G technologies indispensable in various domains including social governance, smart living, and production. In essence, 6G technologies will enable the intelligence of physical entities and the digitalization of practical environments, permeating all aspects of our society.

5.1. *6G visions and requirements*

The goal for 6G systems is to provide unparalleled reliability with minimal latency, high availability, and the ability to support a massive number of devices simultaneously. Although the exact architecture of 6G networks is still evolving, there are several key features and technologies that are expected to shape the future of wireless connectivity. Fig. 5 provides an overview of the visions and requirements for 6G.

i. High-speed connectivity and throughput: 6G networks are anticipated to provide remarkable speeds of up to 1 terabit per second (Tbps), surpassing the capabilities of 5 G by a factor of 100. To accomplish this, 6G will leverage higher frequency bands and employ more sophisticated modulation schemes compared to 5 G. Achieving high-speed connectivity in the realm of 6G will necessitate the integration of various advanced technologies such as optimized spectrum utilization, multiple access techniques, beamforming, novel modulation schemes, network densification, and potentially even THz communication (Khanh et al., 2023).

ii. Ultra-reliable and low-latency Communications (URLLC): In order to support real-time applications, 6G networks must deliver ultra-low latency, reducing the data travel time between devices to below a millisecond. This capability will be crucial for ensuring seamless user experiences and enabling time-sensitive interactions. To achieve this, 6G is anticipated to introduce new modulation schemes, including optimized waveforms, specifically designed to prioritize low latency and enhance overall reliability (Liu et al., 2023). In addition, ultra-dense network deploymen, massive MIMO/beamforming, network slicing, edge computing, Quantum communication, and AI-driven optimization (She et al., 2023).

iii. High reliability and availability: To ensure robust performance, 6G networks must exhibit exceptional reliability and availability, allowing them to seamlessly accommodate a vast multitude of devices and users concurrently. These networks can employ self-healing mechanisms to autonomously identify and rectify errors, minimizing the requirement for manual intervention. By leveraging diverse technologies like multiple access techniques and varied routing paths, 6G networks can enhance reliability and availability by establishing redundant and resilient channels for data transmission. Furthermore, redundancy measures should be integrated at every level of the network, encompassing infrastructure, connectivity, and processing, to bolster overall system resilience (Kharche and Kharche, 2023; Ahmad et al., 2023).

iv. Security: With the proliferation of interconnected devices and applications, the importance of security in 6G networks cannot be overstated. Robust security measures must be embedded at every level, spanning from hardware to software components. Considering the broad spectrum of applications and services supported by 6G, including IoT, smart cities, and autonomous systems, these networks become highly susceptible to cyber threats. Privacy safeguards must be integrated into 6G networks through the utilization of privacy-enhancing technologies like encryption and anonymization, effectively thwarting unauthorized access to sensitive data. Furthermore, ensuring user privacy necessitates

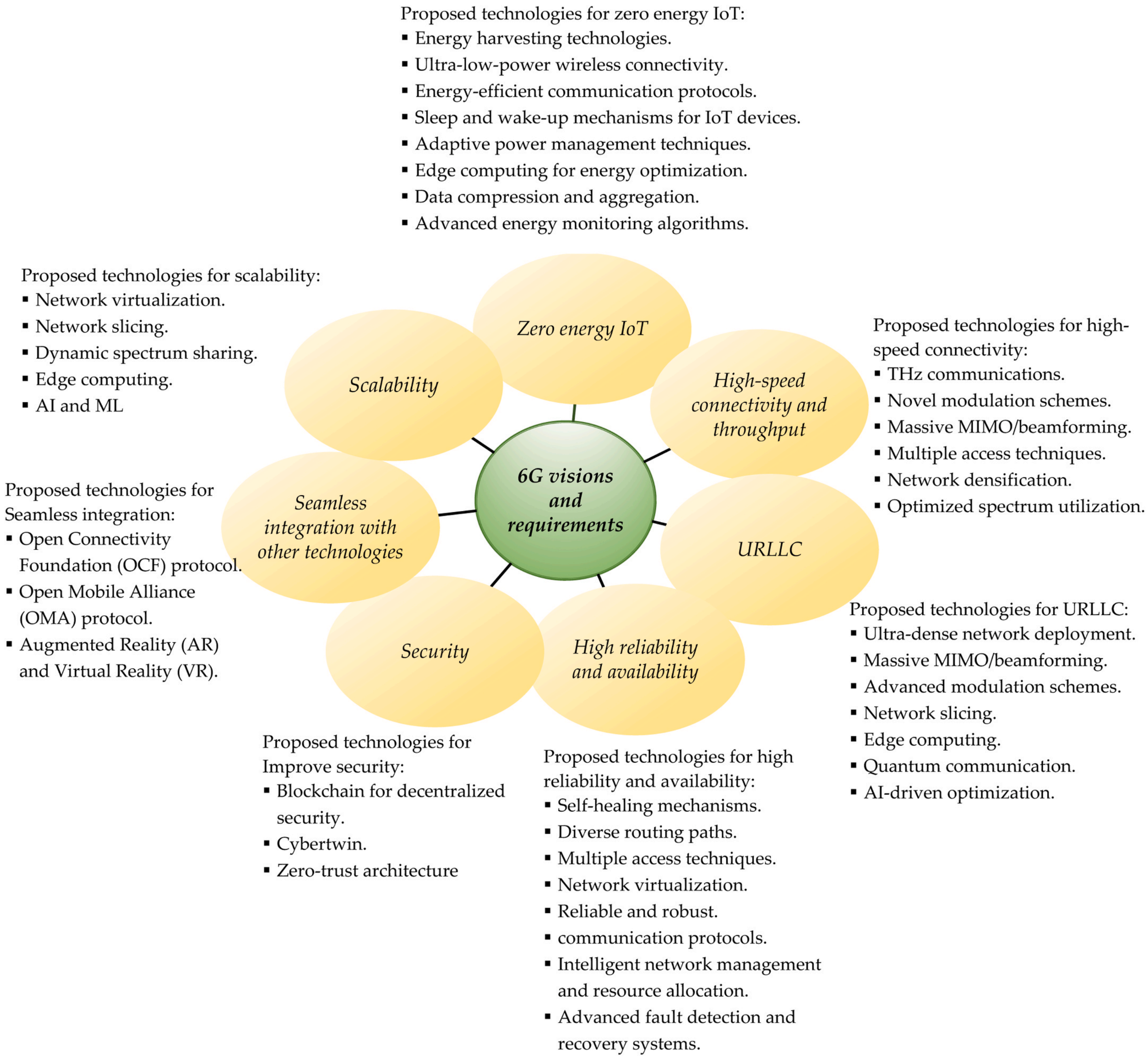

Fig. 5. 6G visions and requirements.

granting individuals control over their data, allowing them to exercise rights such as data access, modification, and deletion. Implementing privacy policies and adhering to data protection regulations can accomplish this. Employing a zero-trust architecture, wherein all devices and networks are treated as potentially compromised, enables stringent access control and authentication mechanisms. Additionally, BC technology holds promise in providing decentralized and tamper-proof security, bolstering secure transactions and deterring unauthorized access (Mitev et al., 2023; Mao et al., 2023).

v. Seamless integration with other technologies: 6G networks have the potential to synergize with various cutting-edge technologies, including the IoT, AI, quantum computing, and edge computing, leading to the emergence of novel services and applications. By adopting an open architecture, 6G networks can seamlessly integrate with these technologies, fostering a flexible and adaptable network infrastructure. Standardized data exchange protocols, such as the Open Connectivity Foundation (OCF) and the Open Mobile Alliance (OMA), can be employed by 6G networks to ensure smooth connectivity and efficient data exchange across devices and systems. This integration of technologies holds the promise of unlocking new realms of innovation and empowering advanced functionalities within the 6G ecosystem (Jahid et al., 2022).

vi. Scalability: Scalability is a crucial aspect of 6G networks, as they must possess the ability to expand and adjust in response to evolving demand and emerging use cases without compromising performance. Network virtualization offers a solution for achieving dynamic scalability in 6G networks by enabling the creation of virtual network functions and services. This virtualization allows for the efficient allocation of resources and the seamless integration of new applications and services that may not yet exist. By embracing scalability, 6G networks can effectively accommodate the diverse and evolving needs of future technologies and ensure optimal performance in a rapidly changing landscape (Jahid et al., 2022).

vii. Zero energy IoT: Within the realm of zero-energy IoT in 6G, one can envision a future where IoT devices establish seamless communication amongst themselves and the cloud through ultra-low-power, high-speed wireless connectivity. Such advancements have the potential to unlock a myriad of novel applications. These applications could harness the capabilities of energy harvesting technologies, such as solar or kinetic energy, to power the IoT devices, thereby reducing or eliminating the need for external power sources (Tariq et al., 2020). Achieving zero energy IoT in the realm of 6G will necessitate the integration of various advanced technologies such as ultra-low-power wireless connectivity, energy-efficient communication protocols, sleep and wake-up mechanisms for IoT devices, adaptive power management techniques, edge computing for localized data processing and reduced energy consumption, data compression and aggregation to minimize energy usage during transmission, advanced energy monitoring and optimization algorithms.

5.2. 6G key enabling technologies

The development of 6G networks relies on several pivotal enabling technologies. The following sections provide a detailed discussion of these technologies, and a summarized overview is presented in Fig. 6. These key enabling technologies hold the promise of delivering ultra-fast data transmission, real-time monitoring and control, enhanced situational awareness, advanced grid analytics, optimized resource allocation, and much more. By harnessing the potential of these technologies, 6G aims to create a truly intelligent and interconnected world, ushering in a new era of connectivity, innovation, and transformative applications.

i. THz spectrum: 6G networks are projected to operate in the THz spectrum (Fig. 7), surpassing the millimeter-wave (mmWave) spectrum used by 5 G. By utilizing the THz frequency range, 6G networks hold the potential for significantly faster data transfer rates. It is estimated that these networks could achieve speeds up to 100 times faster than 5 G, enabling fast communication and data exchange. The utilization of the THz spectrum in 6G networks marks a remarkable advancement in wireless communication technology, opening up new possibilities for high-speed connectivity and supporting the demands of emerging applications and services (Tripathi et al., 2021; Dang et al., 2020).

ii. Massive MIMO and beamforming: Involves deploying a massive number of antennas at base stations, allowing for the simultaneous transmission and reception of multiple data streams to and from multiple users (Fig. 8). This technology offers several advantages for 6G networks. Firstly, Massive MIMO improves spectral efficiency by increasing the capacity of the wireless network. With a large number of antennas, more spatial dimensions are available for transmitting and receiving data, resulting in higher throughput and better utilization of the available spectrum. Secondly, Massive MIMO enhances the network's coverage and signal quality. The use of multiple antennas allows for precise beamforming, enabling targeted transmission

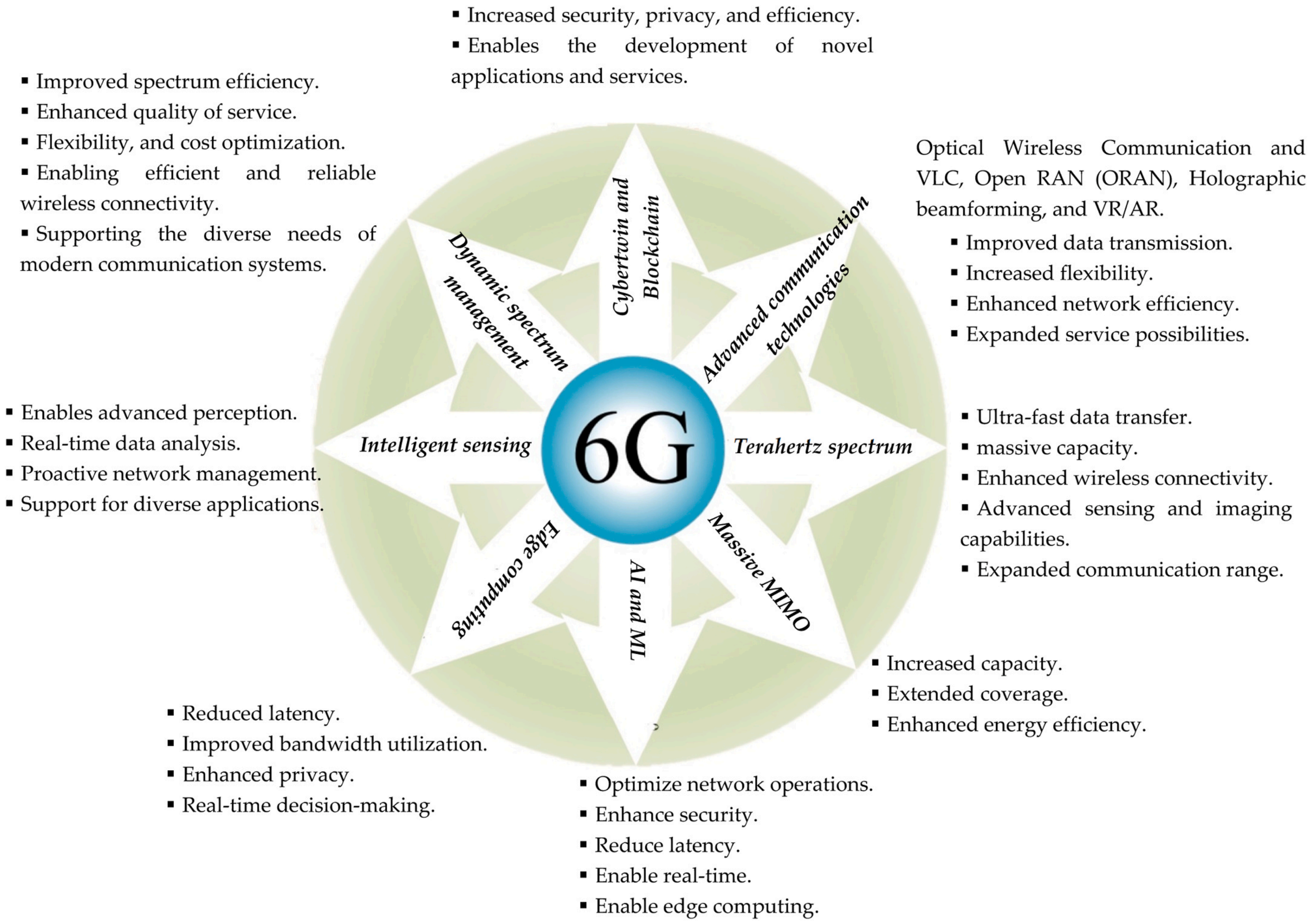

Fig. 6. Key Enabling Technologies for 6G wireless networks.

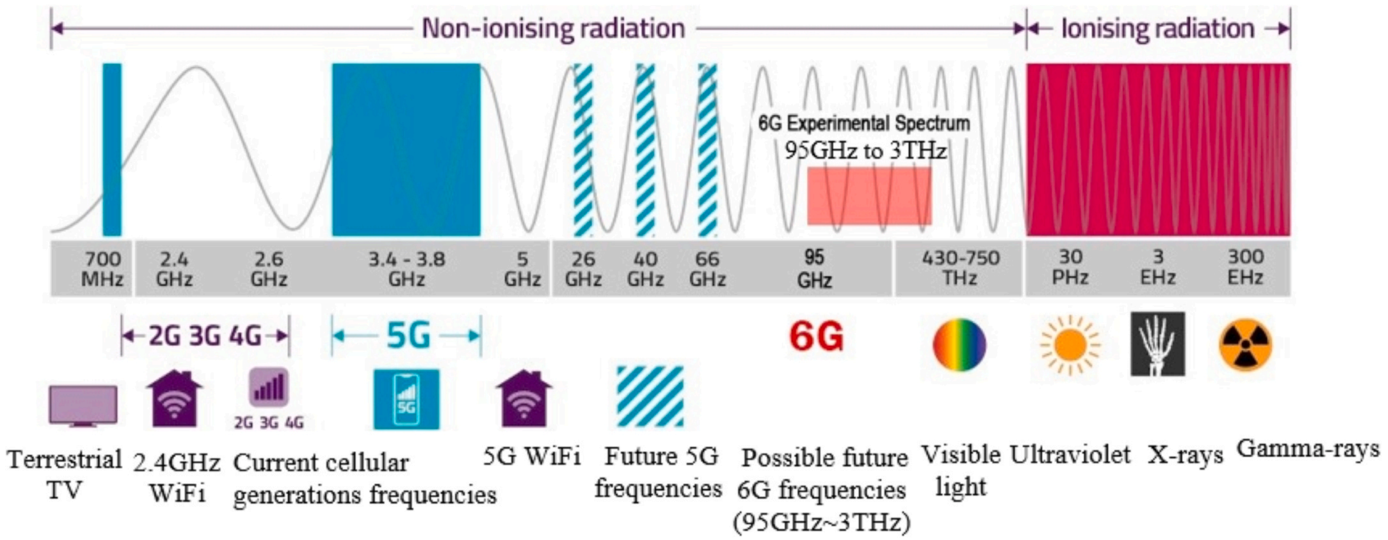

Fig. 7. Electromagnetic and 6G spectrum.

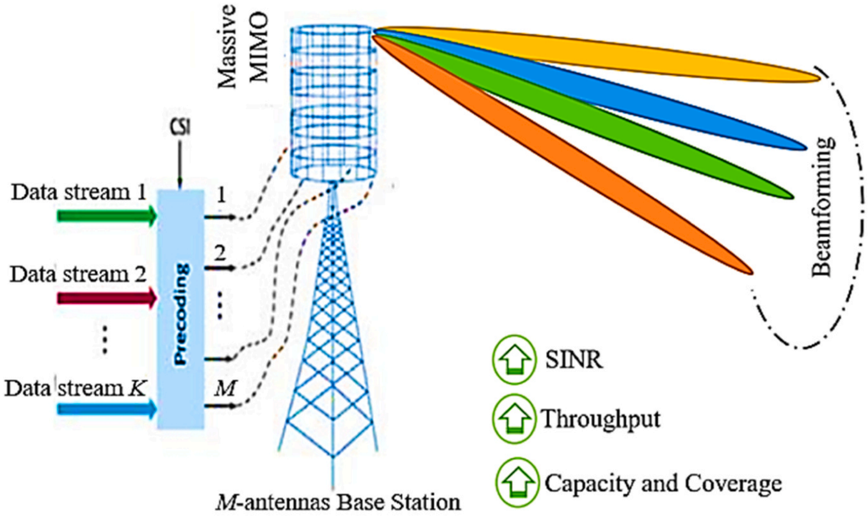

Fig. 8. Massive MIMO and beamforming.

toward specific users or areas. This helps mitigate interference and improves signal strength, even in challenging environments. Thirdly, Massive MIMO enables better energy efficiency. By focusing the transmission energy toward the intended users, it reduces wasteful radiation in non-targeted directions. This results in improved overall energy efficiency, which is crucial for sustainable and green communication systems. Moreover, Massive MIMO facilitates improved user experiences in 6G networks. With the ability to serve a large number of users simultaneously, it supports high-capacity and low-latency communications, enabling advanced applications such as AR, VR, and autonomous systems (Jeon et al., 2021).

iii. AI-enabled networks: AI will play a significant role in shaping the capabilities of 6G networks, enabling them to become more intelligent, adaptive, and efficient. AI-enabled 6G networks leverage the power of ML algorithms and intelligent decision-making to enhance various aspects of network operations and performance. One of the key applications of AI in 6G networks is in network optimization and resource management. AI algorithms can analyze massive amounts of data collected from network devices, users, and applications to identify patterns, predict network demand, and optimize resource allocation. This includes dynamically adjusting bandwidth, prioritizing traffic, and managing network congestion in real-time. By leveraging AI, 6G networks can adapt to changing network conditions and deliver optimal performance. Another area where AI can significantly impact 6G networks is in network security. As the number of connected devices and the complexity of network architectures increase, ensuring robust security becomes critical. AI can help identify and mitigate potential security threats by continuously monitoring network traffic, detecting anomalies, and applying intelligent security measures. AI algorithms can analyze patterns of malicious behavior and proactively respond to emerging threats, enhancing the overall security posture of 6G networks. AI-enabled 6G networks also enable intelligent edge computing. By deploying AI capabilities at the network edge, data processing and decision-making can occur closer to the source, reducing latency and enabling real-time, context-aware applications. AI algorithms can analyze data at the edge, enabling rapid insights and enabling faster response times for time-sensitive applications (Siriwardhana et al., 2021a; Yang et al., 2020).

iv. Edge computing: In 6G networks, edge computing offers several benefits. It reduces latency by processing data closer to its source, enabling real-time applications. Edge computing also optimizes bandwidth usage and network efficiency by minimizing unnecessary data transmission and storage. It enhances privacy by keeping sensitive data within the local network and allows for the implementation of privacy-enhancing techniques. Additionally, edge computing enables real-time decision-making and autonomous operations, improving overall network performance (Siriwardhana et al., 2021b; Al-Ansi et al., 2021). Fig. 9 illustrates the computing technologies and their key attributes.

v. Intelligent sensing: Refers to the system's ability to perceive and comprehend the surrounding environment using diverse sensor technologies, including radar, LiDAR, cameras, and microphones. With the emergence of 6G, intelligent sensing is anticipated to play a crucial role in driving innovative applications and services. These applications span various domains such as autonomous vehicles, smart cities, healthcare, and robotics. For instance, in autonomous vehicles, intelligent sensing enables real-time object detection and recognition, facilitating informed decision-making. To fully realize the potential of intelligent sensing in 6G, extensive research and development efforts are necessary in areas such as sensor fusion, edge computing, and machine learning. Sensor fusion combines data from multiple sensors to achieve a comprehensive understanding of the environment. Edge computing involves processing data at the network edge, reducing latency and improving response times. ML algorithms analyze and interpret sensor data, enabling real-time decision-making (Cui et al., 2021).

vi. Dynamic spectrum management (DSM): Involves the dynamic allocation of radio spectrum resources, considering the prevailing demand and network conditions. By incorporating ML and AI techniques, DSM enables networks to adapt to evolving traffic patterns and flexibly allocate spectrum resources. This adaptive approach enhances efficiency and responsiveness. Furthermore, DSM facilitates the deployment of advanced wireless services like ultra-reliable low-latency communications (URLLC) and massive machine-type communications (mMTC). By allocating spectrum resources in a more optimized manner, DSM ensures that the specific requirements of each service are met, enabling reliable and efficient wireless connectivity for a diverse range of applications (Matinmikko-Blue et al., 2020; Lu and Zheng, 2020).

vii. Cybertwin and Blockchain: A cybertwin refers to a virtual replica or representation of a physical entity. It is a digital counterpart that can interact and simulate the behavior of its physical counterpart. In 6G networks, cybertwins can be utilized for various purposes, including remote monitoring, predictive maintenance, and real-time simulations. By creating a virtual twin, operators can gain insights into the behavior of physical entities and optimize their operations. BC technology, on the other hand, is a decentralized and distributed ledger that records transactions and data across multiple nodes. It offers transparency, immutability, and security, making it suitable for applications in 6G networks. BC can enhance security and trust in various aspects of 6G networks, including data exchange, authentication, and

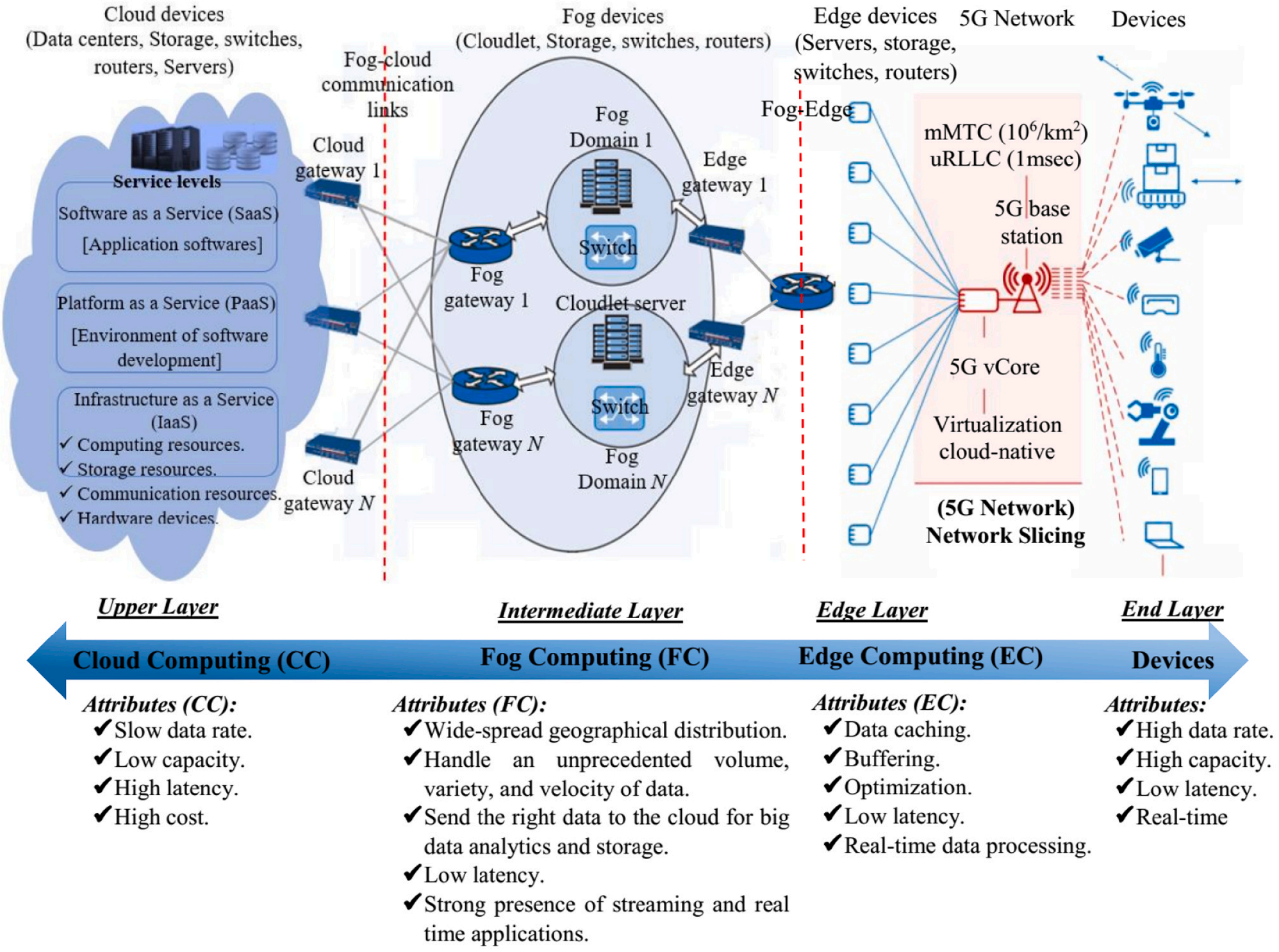

Fig. 9. Computing technologies and their key attributes.

privacy protection. It can enable secure and decentralized transactions, ensure the integrity of data, and provide a tamper-proof record of network activities. BC in 6G networks can support secure P2P interactions, enable secure identities, and facilitate trusted data sharing among multiple parties. The combination of cybertwins and BC in 6G networks can lead to innovative applications and enhanced security. Cybertwins provide a digital representation and simulation of physical entities, enabling real-time monitoring and optimization. BC technology ensures secure and trusted interactions among different entities in the network, safeguarding data and transactions (Juneja et al., 2021; Jahid et al., 2023). Together, cybertwins and BC contribute to the development of intelligent and secure 6G networks.

viii. Network Slicing: Network slicing is a key concept in next-generation networks, including Beyond 5 G (B5G) and 6G. It refers to the ability to partition a physical network infrastructure into multiple logical and independent virtual networks, each tailored to specific requirements and use cases. Network slicing enables the allocation of dedicated resources and customized network configurations to meet the diverse needs of various applications, services, and industries (Xu et al., 2020). Fig. 10 illustrates an overview of the approach to network slicing.

In the context of B5G and 6G, network slicing offers several advantages:

1) Enhanced Flexibility: Network slicing allows for dynamic resource allocation and configuration, enabling networks to adapt to changing demands and requirements. It provides the flexibility to customize

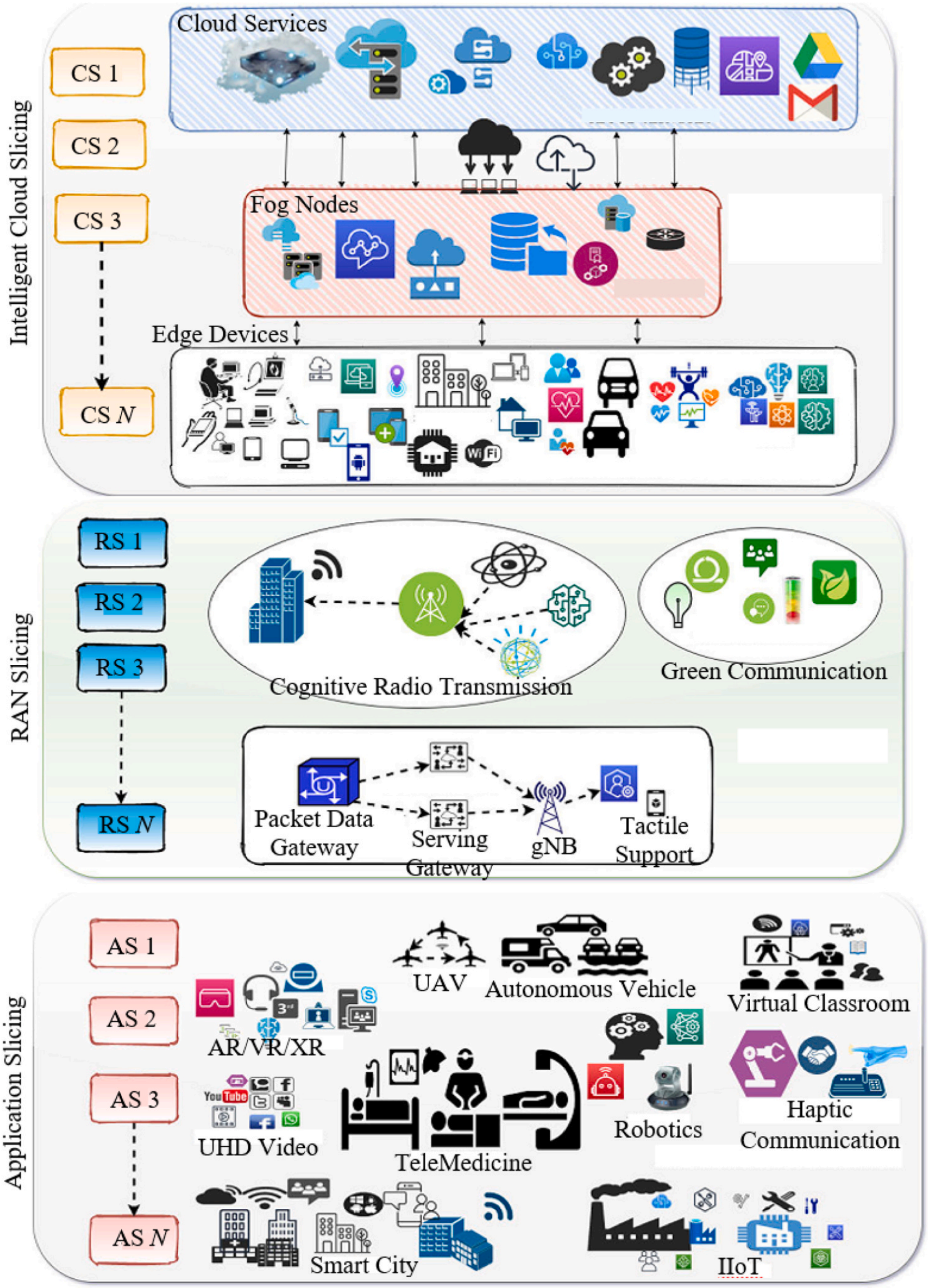

Fig. 10. An overview of the approach to network slicing.

network parameters such as bandwidth, latency, reliability, and security to meet the specific needs of different applications.

2) Improved Service Quality: By dedicating network slices to specific services or industries, B5G and 6G networks can ensure superior service quality and performance. Slices can be optimized to provide low latency, high bandwidth, and reliable connectivity, meeting the stringent requirements of applications such as autonomous vehicles, AR, and industrial automation.
3) Efficient Resource Utilization: Network slicing enables efficient utilization of network resources by allowing multiple virtual networks to coexist on a shared physical infrastructure. This ensures that resources are allocated based on demand, maximizing capacity utilization and minimizing resource wastage.
4) Isolation and Security: Each network slice operates in isolation from others, providing enhanced security and privacy. Slices can be isolated at the network level, ensuring that data and traffic from one slice are isolated from others, thus minimizing the risk of unauthorized access or interference.
5) Industry-Specific Customization: B5G and 6G networks can provide tailored network slices to address the specific needs of various industries, such as healthcare, transportation, energy, and manufacturing. This customization allows industries to leverage the full potential of advanced network capabilities and optimize their operations accordingly.
6) Monetization Opportunities: Network slicing opens up new monetization opportunities for network operators by offering differentiated services to various verticals. It enables the creation of specialized service packages and pricing models based on the unique requirements of each slice, allowing operators to cater to specific industries and applications.

i. Advanced communication technologies: Play a crucial role in the development of 6G networks, enabling higher data rates, improved coverage, and enhanced user experiences. This point will discuss briefly three key technologies: Optical Wireless Communication and Visible Light Communication (VLC), Open RAN (ORAN), and Holographic Beamforming.

Optical Wireless Communication (OWC) is a technology that utilizes light waves for data transmission. It offers several advantages such as high bandwidth, low latency, and immunity to electromagnetic interference. Within OWC, Visible Light Communication (VLC) utilizes light-emitting diodes (LEDs) to enable data communication. VLC can be used in indoor environments, such as offices and homes, to provide wireless connectivity through existing lighting infrastructure. VLC offers the potential for high-speed and secure data transmission, with applications ranging from internet access to indoor positioning systems (Jahid et al., 2022).

Open RAN (ORAN) is a concept that aims to disaggregate and virtualize the components of traditional Radio Access Network (RAN) architecture. ORAN promotes interoperability and vendor-neutral interfaces, allowing for a more flexible and open network ecosystem. By decoupling hardware and software components, ORAN enables operators to select best-of-breed solutions from different vendors, promoting innovation and reducing dependency on a single supplier. This technology fosters competition, lowers deployment costs, and accelerates the development of advanced features and services in 6G networks (Masaracchia et al., 2023).

Holographic beamforming is an advanced beamforming technique that uses holography principles to manipulate and control radio waves. It enables dynamic shaping and steering of beams, allowing for efficient use of spectrum resources and enhanced coverage. Holographic beamforming can overcome limitations of traditional beamforming techniques, such as narrow beamwidth and fixed beam patterns. By adapting the beam shape and direction in real-time, holographic beamforming improves signal quality, reduces interference, and enhances overall network performance. This technology is particularly useful in scenarios with high user density and dynamic mobility patterns, such as crowded urban areas and transportation systems (Huang et al., 2020).

AR, VR, and Extended Reality (ER) are immersive technologies that are expected to be enhanced and integrated into 6G networks. These technologies provide users with immersive and interactive experiences by blending the digital and physical worlds. In 6G, AR, VR, and ER applications can benefit from higher data rates, lower latency, and improved network reliability. This can enable more realistic and seamless experiences, such as lifelike virtual environments, interactive augmented content, and immersive gaming. Furthermore, the integration of AI and ML in 6G networks can enhance the capabilities of AR, VR, and ER, enabling real-time object recognition, spatial mapping, and personalized experiences (de Souza Cardoso et al., 2020).

6. Potential applications of 6G in smart energy grid management

The advent of 6G technology is anticipated to revolutionize various aspects of our lives, enabling new applications and services. Fig. 11 provides an overview of some potential applications that could be enabled by 6G technology. However, this study will pay attention and focus towards exploring the potential applications of 6G technology specifically in the realm of SEGM.

The advent of 6G wireless networks brings forth a range of transformative opportunities for SEGM. With its advanced capabilities in terms of speed, capacity, latency, and reliability, 6G has the potential to revolutionize the way we monitor, control, and optimize energy systems. In this section, we explore the potential technologies of 6G for SEGM and the benefits they can bring. At the end, Table 6 summarizes the potential technologies of 6G that can be used to improve SEGM.

6.1. Real-time monitoring and control

Many grid management systems face challenges in terms of real-time situational awareness, which can impede operators' ability to effectively monitor and respond to dynamic changes in the grid. This limitation can hinder the efficient management of the variability and intermittency associated with renewable energy generation, often resulting in conservative approaches that underutilize renewable energy resources. However, the advent of 6G networks brings promising solutions. These networks provide ultra-low latency and high-speed communication, enabling real-time monitoring and control of grid operations. With this capability, grid operators gain instant visibility into the status of renewable energy generation, power demand, and grid conditions. Real-time data empowers operators to make prompt decisions, respond to fluctuations in renewable energy generation, and ensure grid stability and reliability. In the context of 6G networks, various techniques can be leveraged to enhance real-time monitoring and control capabilities. In addition, Table 3 summarizes the potential 6G technologies that can be used to improve real-time monitoring and control in smart energy grids.

6.1.1. AI and ML

AI and ML algorithms can analyze vast amounts of data from various grid sensors and devices to identify patterns, detect anomalies, and optimize grid performance. These techniques enable predictive maintenance, fault detection, and DR, enhancing real-time monitoring and control capabilities (Mazhar et al., 2023; Aslam et al., 2021). Herein, a discussion on how AI and ML enhance smart grid operations:

i. Predictive Maintenance: AI and ML algorithms can analyze historical and real-time data from grid assets to identify patterns and predict equipment failures. By detecting potential issues in advance, operators can schedule maintenance activities proactively, reducing downtime and optimizing asset performance (Kumar et al., 2023).

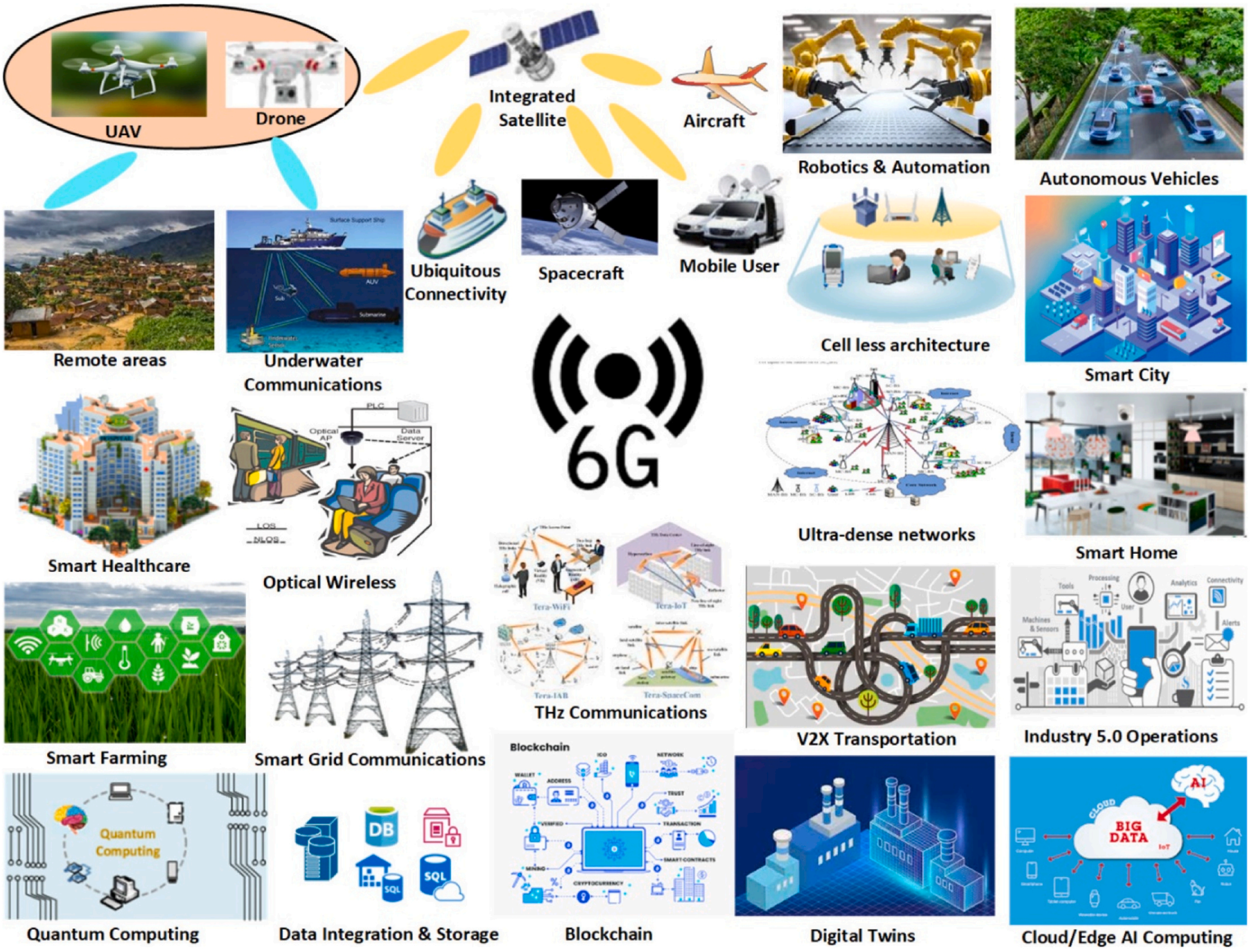

Fig. 11. An overview of some potential use cases and applications for 6G networks.

ii. DR: AI and ML can analyze historical consumption patterns, weather forecasts, and pricing data to predict electricity demand. This information enables utilities to implement DR programs that incentivize consumers to adjust their electricity usage during peak periods, optimizing load distribution and grid stability (Mhlanga, 2023).

iii. Anomaly Detection: AI and ML techniques can detect anomalies in grid data, such as abnormal power consumption or equipment behavior. These algorithms can automatically flag and investigate potential abnormalities, enabling operators to identify and address issues promptly, improving grid reliability and security (Saheb et al., 2022).

iv. Optimization and Control: AI and ML algorithms can optimize grid operations by analyzing real-time data and making intelligent decisions. For example, ML algorithms can optimize energy dispatch strategies, grid configuration, and power flow to minimize losses and maximize the utilization of renewable energy resources (Kumar et al., 2023).

v. Energy Forecasting: AI and ML can improve the accuracy of energy forecasting, considering factors like weather conditions, consumer behavior, and energy generation from renewables. Accurate energy forecasting helps utilities in efficient resource planning, reducing costs, and ensuring grid stability (Arumugham et al., 2023).

vi. Grid Resilience and Self-Healing: AI and ML techniques can enable self-healing capabilities in the smart grid. By continuously monitoring grid data, these algorithms can detect faults or disruptions and automatically reroute power flows, isolate affected areas, and restore service, ensuring grid resilience and minimizing downtime (Saheb et al., 2022).

vii. Energy Theft Detection: AI and ML algorithms can identify patterns indicative of energy theft or meter tampering by analyzing consumption data. This helps utilities detect and prevent revenue losses due to illegal activities (Simoes et al., 2023).

6.1.2. *IoT and intelligent sensing*

The integration of IoT and intelligent sensing technologies in smart grids enable real-time data collection, analysis, and control, leading to optimized energy distribution, improved grid reliability, enhanced integration of RES, and increased consumer engagement in energy management (Goudarzi et al., 2022; Kirmani et al., 2022; Abir et al., 2021). These technologies are vital in transforming traditional power grids into intelligent and sustainable energy systems. Herein, discuss in more detail how these technologies contribute to various aspects of smart grid management:

i. Real-time data collection and analysis: IoT devices, such as smart meters, sensors, and actuators, are deployed throughout the grid to collect real-time data on energy consumption, generation, and

Table 3
Potential 6G technologies for improving real-time monitoring and control in smart energy grids.

Smart grid requirements	Potential techniques in 6G Networks	Enhancements for smart grids
Real-time monitoring and control	AI and ML	▪ Predictive Maintenance. ▪ Demand Response. ▪ Anomaly Detection. ▪ Optimization and Control. ▪ Energy Forecasting. ▪ Grid Resilience and Self-Healing. ▪ Energy Theft Detection.
	IoT and intelligent sensing	▪ Real-time data collection and analysis. ▪ Energy optimization. ▪ Fault detection. ▪ Predictive maintenance. ▪ Integration of RES. ▪ Grid resilience. ▪ Outage management. ▪ Consumer engagement.
	Edge computing	▪ Real-time data processing. ▪ Distributed energy management. ▪ Intelligent control. ▪ Secure data filtering. ▪ Offline operations.
	Visualization technologies (VR/AR)	▪ Real-time data visualization. ▪ Interactive control interfaces. ▪ Enhanced situational awareness. ▪ Remote monitoring and control. ▪ Simulation and predictive analysis.

grid conditions. This data is transmitted to centralized control systems for analysis. Intelligent sensing algorithms can analyze the collected data to identify patterns, trends, and anomalies, providing valuable insights into energy usage patterns, load profiles, and equipment performance (Kirmani et al., 2022).

ii. Energy optimization and load management: By leveraging IoT devices and intelligent sensing, smart grids can optimize energy distribution and load management. Real-time data on energy demand and supply allows for dynamic load balancing and efficient utilization of available energy resources. Intelligent algorithms can analyze energy consumption patterns and make predictions to optimize energy delivery and reduce peak demand (Abir et al., 2021).

iii. Fault detection and predictive maintenance: IoT devices and intelligent sensing technologies enable continuous monitoring of grid equipment and infrastructure. By detecting anomalies, such as abnormal energy consumption or voltage fluctuations, potential faults or failures can be identified in real-time. Predictive maintenance models can be developed using ML algorithms to anticipate equipment failures and schedule maintenance activities, reducing downtime and improving grid reliability (Ahmad and Zhang, 2021).

iv. Integration of RES: IoT devices and intelligent sensing play a crucial role in integrating RES into the grid. By monitoring the performance of solar PV, WTs, and other renewable energy systems, smart grids can optimize their utilization. Real-time data on energy generation, weather conditions, and energy storage levels enables the efficient integration of RES into the grid, ensuring a smooth transition to a more sustainable energy mix (Qays et al., 2023).

v. Grid resilience and outage management: IoT devices and intelligent sensing enhance grid resilience by providing real-time information on grid conditions and detecting potential issues, such as power outages or grid disturbances. This enables swift response and efficient outage management, reducing the duration and impact of disruptions. Intelligent algorithms can analyze data from multiple sources to identify the cause of outages and enable quick restoration of power (Alomar, 2023).

vi. Consumer engagement and energy efficiency: IoT devices, such as smart thermostats, smart appliances, and EMS, allow consumers to actively participate in energy management. Real-time energy consumption data and intelligent insights empower consumers to make informed decisions about their energy usage, optimize energy consumption, and reduce costs. With IoT-enabled devices, consumers can remotely monitor and control their energy usage, promoting energy efficiency and sustainability (Ahmad and Zhang, 2021).

6.1.3. *Edge computing*

Edge computing in smart grid applications enables real-time data processing, distributed energy management, intelligent control, secure data filtering, and offline operations. By leveraging edge computing, smart grids become more efficient, responsive, and resilient, leading to improved energy management, reduced downtime, and enhanced grid performance (Minh et al., 2022). In follows a discussion of each point in more detail:

i. Real-time data processing: Edge computing allows for real-time processing and analysis of data at the edge of the network. This is crucial in smart grid applications as it enables immediate decision-making and response to dynamic grid conditions. By processing data locally, latency is minimized, ensuring faster reaction times to grid events and facilitating real-time monitoring and control (Saleem et al., 2023).

ii. Distributed energy management: With edge computing, energy management tasks can be performed at the edge devices themselves, such as smart meters or DERs. This localized energy management enables more efficient utilization of energy resources, optimal load balancing, and better integration of RES. It also reduces the dependency on centralized control systems, leading to increased grid resilience and reliability (Mhlanga, 2023).

iii. Intelligent control of devices and sensors: Edge computing allows for intelligent control and coordination of devices and sensors deployed within the smart grid infrastructure. By leveraging localized computing power, edge devices can autonomously respond to grid conditions and adjust their operations accordingly. For example, smart grid sensors can detect anomalies or faults and trigger immediate actions, such as isolating faulty sections or rerouting power flows (Slama, 2022).

iv. Secure data filtering and analysis: Edge computing enables data filtering and analysis at the edge devices, minimizing the need to transmit large volumes of data to the central cloud servers. This reduces bandwidth requirements and network congestion. Moreover, sensitive data can be processed locally, enhancing data privacy and security. By applying data analytics and ML algorithms at the edge, valuable insights can be derived from the data, enabling predictive maintenance, anomaly detection, and improved grid optimization (Qi and Tao, 2019).

v. Offline operations and grid resiliency: Edge computing allows for localized decision-making and control even in the absence of network connectivity. This means that critical grid operations can continue to function autonomously during network disruptions or outages. By maintaining local processing capabilities, edge devices can perform essential functions and ensure uninterrupted grid operations, enhancing the resiliency and reliability of the smart grid (Qiu et al., 2020).

6.1.4. Visualization technologies (VR/AR)

The integration of VR/AR technologies in real-time monitoring and control in smart grids enhances operators' situational awareness, provides interactive control interfaces, facilitates remote monitoring, and enables simulation-based analysis (Li et al., 2018). These capabilities contribute to more efficient grid operations, improved response times, and enhanced grid reliability (Xiao et al., 2023).

i. Real-time data visualization: VR/AR can provide real-time visual representations of grid data, such as power flow, voltage levels, and equipment status. Operators can view this data in an immersive and intuitive manner, allowing them to quickly identify any anomalies or issues that require immediate attention. This enables faster decision-making and response to grid events, improving the overall reliability and stability of the grid.
ii. Interactive control interfaces: VR/AR interfaces can provide interactive control panels and dashboards, allowing operators to monitor and control grid elements in real-time. They can manipulate virtual switches, adjust settings, and simulate various scenarios to evaluate the impact of their actions on the grid. This facilitates efficient control and optimization of grid operations, enabling operators to respond promptly to changes in demand, renewable energy generation, or grid disturbances.
iii. Enhanced situational awareness: By overlaying real-time grid data onto the physical environment, AR technology enhances situational awareness for operators. They can see vital information, such as live sensor readings, equipment statuses, and alarm notifications, superimposed on their field of view. This helps operators quickly identify the location and severity of issues, enabling them to take immediate corrective actions.
iv. Remote monitoring and control: VR/AR technologies enable remote monitoring and control of smart grid infrastructure. Operators can access real-time data and control interfaces through VR/AR devices, eliminating the need for physical presence at the grid's location. This is particularly useful for large-scale or geographically dispersed grids, as operators can remotely monitor multiple sites, detect anomalies, and intervene as necessary.
v. Simulation and predictive analysis: VR/AR simulations can be used to predict and analyze the behavior of the grid in real-time. By integrating real-time data with simulation models, operators can assess the impact of different scenarios and make informed decisions. This allows them to optimize grid operations, plan maintenance activities, and proactively address potential issues before they occur.

6.2. Ultra-fast communication and data transmission

Ultra-fast communication and data transmission are fundamental aspects of 6G networks that have the potential to greatly enhance smart grids. With its high data transfer rates and minimal latency, 6G networks can revolutionize smart grids by facilitating real-time monitoring, control, and decision-making processes. This enhanced communication infrastructure allows for the seamless integration of diverse devices and applications within the smart grid ecosystem (renewable energy generators, smart meters, and sensors, without any significant delay), enabling efficient energy management, grid analytics, and the integration of RES (Alsharif et al., 2020). By leveraging the capabilities of 6G networks, smart grids can achieve greater reliability, improved grid stability, and optimized energy distribution, leading to a more sustainable and resilient energy future. In order to achieve ultra-fast data transmission in smart grids using 6G networks, several techniques can be employed as will discuss in the following. In addition, Table 4 present a summary of ultra-fast data transmission 6G techniques.

6.2.1. THz spectrum

The THz spectrum is expected to play a significant role in the communication infrastructure of 6G networks, including its application in smart grids. The THz spectrum refers to frequencies ranging from 0.1 to 10 THz, which are much higher than the frequencies used in previous generations of wireless communication (Yap et al., 2022; Abdelwahab et al., 2019). In the context of smart grids, the use of THz spectrum in 6G offers several advantages:

i. Ultra-Fast Data Transfer: The THz spectrum provides significantly higher bandwidth compared to lower frequency bands, enabling ultra-fast data transfer rates. This allows for the seamless transmission of large volumes of data in real-time, which is essential for supporting various applications in smart grids.
ii. Increased Capacity: The THz spectrum offers a vast amount of available bandwidth, which translates into increased capacity for smart grid communication. This enables the concurrent transmission of massive amounts of data, such as sensor readings, monitoring information, and control signals, supporting the diverse requirements of smart grid operations.
iii. Reduced Latency: The use of THz spectrum in 6G networks helps to minimize latency, the time delay between data transmission and reception. By reducing latency, real-time communication between smart grid devices and systems is achieved, enabling

Table 4
Ultra-fast data transmission 6G techniques for smart energy grids.

Smart grid requirements	Potential techniques in 6G Networks	Enhancements for smart grids
Ultra-Fast Communication and Data Transmission	THz spectrum	▪ Ultra-fast data transfer. ▪ Increased capacity. ▪ Reduced latency. ▪ Support for high-density deployments.
	Massive MIMO and beamforming	▪ Enhanced data handling capacity. ▪ Extended Coverage for devices that are located in remote or challenging environments. ▪ Energy Efficiency.
	Edge computing	▪ Real-time monitoring. ▪ Localized data processing. ▪ Enhanced privacy.
	Network slicing	▪ Real-time monitoring. ▪ Efficient resource allocation. ▪ Enhanced security. ▪ Seamless scalability.
	DSA	▪ Improved network performance. ▪ Enhanced grid management. ▪ Efficient resource utilization.
	OWC and VLC	▪ High-speed capabilities. ▪ Improved security and reliability. ▪ Support for high-density deployments. ▪ Energy efficiency. ▪ Scalability, and flexibility. ▪ Significantly enhance the communication infrastructure of smart grids.

instant response to grid events and facilitating time-critical applications such as fault detection, load balancing, and grid optimization.

iv. Support for High-Density Deployments: The THz spectrum allows for high-density deployments of smart grid devices and sensors. The increased bandwidth enables seamless connectivity between a large number of devices, facilitating comprehensive monitoring and control of the grid. This is particularly beneficial in urban environments where a dense deployment of sensors and devices is required.

However, the use of THz spectrum in 6G networks also presents some challenges. THz waves have shorter wavelengths and are more susceptible to signal attenuation and blockage by obstacles such as buildings and vegetation. Overcoming these challenges requires advancements in antenna technology, beamforming techniques, and signal propagation models to ensure reliable and robust communication in smart grid deployments (Shafie et al., 2022).

6.2.2. *Massive MIMO and beamforming*

Massive MIMO and beamforming are key technologies employed in 6G networks to enhance communication in smart grids. Massive MIMO involves using a large number of antennas at the base station, increasing capacity and spectral efficiency. In smart grids, it enables efficient communication with devices like smart meters, sensors, and distributed energy resources, improving coverage and signal quality for reliable data transmission. On the other hand, beamforming focuses radio waves in specific directions, creating narrow and highly directional beams. The beamforming technique establishes reliable communication links between the base station and grid devices, even in challenging environments (remote and rural areas) (Hassan and Fernando, 2017; Molisch et al., 2017). By combining Massive MIMO and beamforming in 6G networks for smart grids, the following benefits can be achieved:

i. Increased Capacity: Massive MIMO enables the concurrent transmission of data to multiple devices, improving the overall capacity of the network. This is particularly valuable in smart grids, where a large number of devices generate and exchange data in real-time. The increased capacity ensures that the grid can handle the growing volume of data, supporting applications such as real-time monitoring, DR, and grid optimization.

ii. Extended Coverage: Beamforming enables the focusing of the transmitted signals, extending the coverage range of the base station. This is particularly useful in smart grid deployments where devices may be located in remote or challenging environments. The extended coverage ensures that devices in these areas can maintain reliable and efficient communication with the grid infrastructure, facilitating comprehensive monitoring and control of the grid.

iii. Energy Efficiency: Massive MIMO and beamforming techniques can improve energy efficiency in smart grids. By focusing the transmission towards specific devices, beamforming reduces the energy consumption required for communication, as the signals are directed precisely to the intended recipients. Additionally, Massive MIMO allows for more efficient resource allocation, reducing interference and optimizing energy usage. This leads to overall energy savings in the smart grid network.

6.2.3. *Edge computing*

Edge computing in 6G networks plays a vital role in enhancing smart grid operations. It facilitates real-time monitoring, control, and decision-making by leveraging ultra-fast communication and data transmission capabilities. By reducing latency and improving response times, edge computing enables efficient management of the smart grid, empowering it with real-time capabilities discussed in section 4.1.3.

With ultra-fast communication in 6G networks, edge computing in the smart grid can handle large volumes of data generated by numerous devices, such as smart meters, sensors, and RES. The data can be processed and analyzed at the edge devices, eliminating the need to transmit all data to a centralized cloud or data center. This reduces network congestion, optimizes bandwidth utilization, and improves overall efficiency (Slama, 2022).

Edge computing also enables localized data processing and analysis, which enhances privacy and security in the smart grid. Sensitive data can be processed and stored locally, minimizing the risk of data breaches or unauthorized access. Additionally, edge devices can implement privacy-enhancing techniques, such as data anonymization and encryption, further protecting sensitive information (Qi and Tao, 2019).

Furthermore, edge computing facilitates real-time decision-making and autonomous operations in the smart grid. By processing data locally, edge devices can analyze information, detect anomalies, and respond to events without relying on constant communication with a centralized system. This enables faster response times, improved grid stability, and the ability to adapt to dynamic changes in power generation, demand, and grid conditions (Slama, 2022).

6.2.4. *Network slicing*

Network slicing is an innovative feature of 6G networks that holds immense potential for enhancing smart grid operations. In the context of smart grids, network slicing refers to the partitioning of the network infrastructure into multiple virtual network slices, each customized to meet the specific requirements of different smart grid applications and services. By utilizing network slicing in a smart grid, the network resources, such as bandwidth, latency, and quality of service, can be dynamically allocated based on the demands of various grid services. This ensures that critical grid operations, such as real-time monitoring, control, and DR, receive dedicated network resources and optimal performance (Xu et al., 2020). For example, network slicing can allocate high-bandwidth and low-latency resources to support real-time data transmission from sensors, smart meters, and other grid devices. This enables faster and more accurate data collection, facilitating real-time monitoring of grid conditions, energy consumption, and asset performance. Moreover, network slicing allows for efficient resource utilization, as the smart grid can allocate network resources based on the specific needs of each application. This means that resources are not wasted on applications that do not require high-speed or low-latency connections, while critical applications receive the necessary network support (Zhang, 2019). Additionally, network slicing provides enhanced security and isolation for smart grid applications. Each network slice operates independently, with its own dedicated resources and security measures. This isolation helps prevent unauthorized access, data breaches, and ensures the integrity of critical grid operations (Xu et al., 2020).

6.2.5. *Dynamic spectrum access (DSA)*

Dynamic Spectrum Access (DSA) is a transformative feature of 6G networks that revolutionizes the management of smart electrical grids. It enables intelligent and real-time utilization of available spectrum resources based on the changing needs of the grid. In the context of smart electrical grids, DSA empowers grid devices and applications to autonomously select the most suitable spectrum bands and channels for their communication requirements. This dynamic allocation of spectrum resources ensures optimal utilization and efficient sharing among different grid devices and applications. The implementation of DSA in smart electrical grid management systems enhances communication and data transmission capabilities, enabling real-time monitoring, control, and coordination of grid devices such as smart meters, sensors, and DERs (Iyer, 2023).

DSA offers several advantages for smart electrical grids. Firstly, it addresses the diverse and dynamic spectrum requirements within the grid by allocating dedicated and prioritized spectrum resources to critical applications such as grid monitoring, load balancing, and fault detection. This ensures low-latency and reliable communication for these essential grid functions. Secondly, DSA promotes the coexistence of multiple wireless technologies within the smart electrical grid, facilitating efficient and interference-free communication between different wireless standards used by grid devices and systems (Iyer, 2022).

The dynamic nature of DSA allows the smart electrical grid management system to adapt to changing environmental and network conditions. During periods of high demand or network congestion, DSA can allocate additional spectrum resources to accommodate increased communication requirements, ensuring optimal performance and reliability of the grid management system. Moreover, DSA improves spectrum utilization and efficiency within the smart electrical grid by allowing devices to opportunistically access unused or underutilized spectrum bands, minimizing wastage and maximizing network capacity. Furthermore, DSA promotes spectrum sharing and coordination among different stakeholders in the smart electrical grid ecosystem. It enables efficient spectrum management, fostering collaboration between grid operators, service providers, and other participants, and ensuring fair and equitable access to spectrum resources. This optimization of spectrum allocation and utilization enhances the overall operation of the electrical grid, leading to improved network performance and more efficient utilization of resources (Akyildiz et al., 2020).

6.2.6. *Optical wireless communication (OWC) and visible light communication (VLC)*

OWC and VLC enable ultra-fast communication and data transmission in smart grids through their high-speed capabilities. By utilizing the visible light spectrum or other optical frequencies, these technologies can achieve transmission rates that surpass traditional wireless communication methods (Jahid et al., 2022). This allows for rapid and efficient exchange of data between various grid devices, such as smart meters, sensors, and control systems. Moreover, OWC and VLC offer several advantages for smart grid applications (Zhou et al., 2020).

i. Security and reliability: OWC and VLC offer improved security and reliability. The use of light as a communication medium minimizes the risk of interference from external sources, ensuring secure and reliable data transmission within the grid infrastructure. Additionally, OWC and VLC can provide better coverage and connectivity in challenging environments, such as areas with electromagnetic interference or radio frequency congestion.

ii. High-density deployments: OWC and VLC in smart grids the ability to support high-density deployments. These technologies can accommodate a large number of devices within a limited area, making them suitable for scenarios with a high concentration of grid devices. This enables efficient communication and coordination among numerous devices, facilitating real-time monitoring, control, and management of the grid.

iii. Energy efficiency: OWC and VLC contribute to energy efficiency in smart grids. By utilizing light as a communication medium, these technologies consume less power compared to traditional wireless communication methods. This leads to reduced energy consumption and improved sustainability in the operation of smart grid systems.

iv. Scalability and flexibility: OWC and VLC also offer scalability and flexibility in smart grids. These technologies can be easily integrated into existing infrastructure, allowing for seamless adoption and deployment. Additionally, they can coexist with other wireless communication technologies, complementing and enhancing the overall communication capabilities of the smart grid network.

6.3. *Cybersecurity*

Grid resilience and cybersecurity are essential for the effective operation of smart electrical grids, and 6G networks offer valuable solutions in these areas. In 6G, various techniques can be applied to enhance grid resilience and cybersecurity. These include the use of secure communication protocols, network slicing, multi-layered security approaches, intrusion detection and prevention systems, advanced authentication mechanisms, BC technology, and the implementation of cybertwin concepts. By implementing these techniques, 6G networks can significantly bolster grid resilience and cybersecurity in smart electrical grids. These measures ensure the secure and reliable transmission of grid data, safeguard against cyber threats, and enable efficient grid management. This study focuses on the most two key techniques in this domain: BC and cybertwin, which hold immense promise in enhancing grid resilience and cybersecurity in the context of 6G networks (Song et al., 2023; Mololoth et al., 2023; Sifat et al., 2022). Table 5 present a summary of grid resilience and cybersecurity 6G techniques.

6.3.1. *Blockchain technology*

BC technology has emerged as a transformative solution with the potential to revolutionize various industries, including the management of smart electrical grids. In the context of smart grid management, BC offers a decentralized and transparent platform that enables secure and efficient data exchange, authentication, and coordination among different stakeholders (Mololoth et al., 2023). By leveraging the features of immutability, transparency, and consensus, BC provides a robust foundation for enhancing the resilience, security, and efficiency of smart electrical grid operations (Afzal et al., 2022). Fig. 12 shown the resource management framework in 6G networks that is enabled by BC technology.

Using a BC in the smart electrical grids can achieve several benefits, including:

i. Enhanced Security: BC provides a decentralized and immutable platform for securing critical grid data and transactions. It eliminates the need for a centralized authority, reducing the risk of cyber attacks and unauthorized access. The cryptographic algorithms used in BC ensure the integrity and confidentiality of grid data, making it highly secure (Ghiasi et al., 2023).

ii. Improved Grid Efficiency: BC facilitates efficient P2P transactions and data sharing among various grid participants, including consumers, generators, and grid operators. Smart contracts, which are self-executing agreements recorded on the BC, automate processes such as energy trading, billing, and grid management. This automation streamlines operations, reduces costs, and minimizes human error (Mollah et al., 2020).

Table 5
The key cybersecurity 6G techniques for smart energy grids.

Smart grid requirements	Potential techniques in 6G Networks	Enhancements for smart grids
Grid resilience and cybersecurity	Blockchain (BC)	▪ Enhanced Security. ▪ Improved Grid Efficiency. ▪ Enhanced Grid Resilience. ▪ Transparent and Auditable Transactions. ▪ P2P Energy Trading. ▪ Grid Data Management.
	Cybertwin	▪ Predictive maintenance and fault detection. ▪ Advanced analytics and optimization. ▪ Training and testing. ▪ Grid resiliency and emergency planning. ▪ Grid cybersecurity. ▪ Decision-making support.

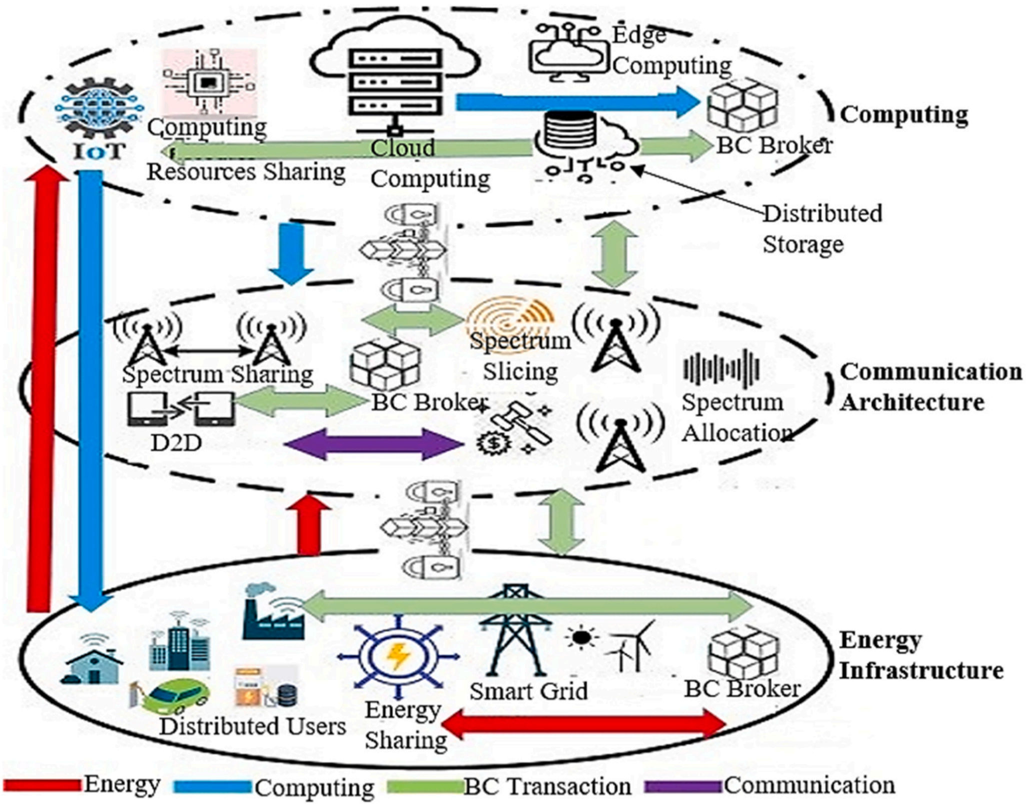

Fig. 12. A resource management framework in 6G networks that is enabled by BC technology.

iii. Enhanced Grid Resilience: BC technology introduces redundancy and fault tolerance in smart grids. The decentralized nature of the BC network ensures that data and transactions are distributed across multiple nodes, making it resilient to single points of failure. In the event of a disruption or attack, the grid can continue to operate seamlessly, ensuring uninterrupted power supply and grid stability (Mollah et al., 2020).

iv. Transparent and Auditable Transactions: The transparency provided by BC enables real-time tracking and auditing of grid transactions. All transactions recorded on the BC are visible to participants, ensuring accountability and trust. This transparency helps prevent fraudulent activities and ensures fair and reliable energy trading (Sifat et al., 2022).

v. P2P Energy Trading: BC enables direct P2P energy trading between consumers and producers in a decentralized manner. Smart contracts facilitate automated and transparent energy transactions, allowing consumers to buy energy directly from nearby RES. This P2P energy trading promotes energy efficiency, reduces dependency on centralized utilities, and encourages the use of renewable energy (Gawusu et al., 2022).

vi. Grid Data Management: BC provides a secure and efficient platform for managing grid data, including meter readings, energy consumption, and grid performance data. By securely storing and sharing this data, BC enables grid operators and other stakeholders to make informed decisions based on accurate and reliable information (Jahid et al., 2023).

6.3.2. *Cybertwin technology*

Cybertwin technology is a revolutionary concept that has the potential to transform the management of smart electrical grids. It involves the creation of a virtual replica, known as a "cyber twin," that mirrors the physical grid infrastructure, including devices, sensors, and systems. This virtual replica is constantly updated and synchronized with the real-world grid, providing real-time monitoring, analysis, and control capabilities (Song et al., 2023).

One of the primary advantages of cybertwin technology is its ability to enable predictive maintenance and fault detection in the grid. By analyzing data from the cyber twin, operators can identify potential issues, anomalies, or failures in the grid infrastructure before they occur in the physical system. This proactive approach helps prevent disruptions, reduce downtime, and optimize maintenance schedules, leading to improved grid reliability and operational efficiency (Senthilnathan and Annapoorani, 2019). In addition, cybertwin technology facilitates advanced analytics and optimization algorithms to be applied to the virtual replica of the grid. By leveraging ML and AI techniques, the cyber twin can simulate different scenarios, perform predictive analytics, and optimize grid operations. This includes load balancing, DR, energy optimization, and grid resiliency planning. The insights gained from the cyber twin can guide decision-making and enable more efficient and effective grid management strategies (Jafari et al., 2023). Furthermore, the cyber twin serves as a valuable tool for training and testing purposes. It provides a safe and controlled environment to simulate and evaluate different grid management strategies, response plans, and emergency scenarios. This helps grid operators and technicians develop and refine their skills, validate new technologies, and enhance the overall grid resilience (Olivares-Rojas et al., 2021). Another significant aspect of cybertwin technology is its contribution to grid cybersecurity. By continuously monitoring the cyber twin, operators can detect and respond to potential cyber threats and vulnerabilities in real-time. The cyber twin can act as a sandbox environment to test security measures, validate security patches, and simulate cyber attacks, allowing operators to proactively strengthen the security posture of the physical grid infrastructure (Senthilnathan and Annapoorani, 2019).

The integration of BC technology and cybertwin technology in smart electrical grids brings numerous advantages. It enhances data security, trust, and transparency by providing a decentralized and immutable platform for securing and verifying data. It enables reliable data sharing and collaboration among grid participants, improving grid resilience and reducing the risk of disruptions. The integration streamlines transactions, automates processes through smart contracts, and enables advanced analytics for optimized grid operations. It also facilitates compliance with regulatory frameworks and simplifies auditing processes.

6.4. *Scalability and flexibility*

In order to achieve scalability and flexibility in smart electrical grids, several 6G techniques can be employed. These techniques are designed to accommodate the increasing integration of distributed energy resources, such as rooftop solar PV and small-scale WTs. Here are some of the key 6G techniques that can address scalability and flexibility challenges in smart electrical grids: Table 6.

i. Edge Computing: By utilizing edge computing capabilities, 6G networks can process and analyze data closer to the grid's edge, reducing latency and enabling faster decision-making. This enhances scalability by efficiently handling the growing volume of data generated by DERs and enables real-time grid management.
ii. Virtualization: 6G networks can leverage virtualization techniques to create virtualized infrastructure, enabling the dynamic allocation of resources based on grid demands. This flexibility allows for efficient scaling of resources and supports the integration of new DERs without significant infrastructure modifications.
iii. Network Slicing: Network slicing in 6G allows the creation of virtual, independent network instances tailored to specific applications and services. By allocating dedicated slices for distributed energy resources, grid operators can ensure optimal performance and scalability for different types of energy resources, enhancing flexibility and resource allocation efficiency.
iv. Dynamic Spectrum Access: Dynamic spectrum access techniques enable smart electrical grids to utilize available spectrum resources more efficiently. By dynamically allocating spectrum bands based on real-time demand, 6G networks can enhance scalability and flexibility in communication between grid devices and infrastructure.
v. IoT Integration: The integration of IoT devices in 6G networks enables the seamless connectivity and control of distributed energy resources. IoT sensors and devices provide real-time data on energy generation, consumption, and grid conditions, allowing grid operators to optimize resource allocation and enhance scalability based on current grid demands.
vi. Advanced Analytics and AI: By employing advanced analytics and AI algorithms, 6G networks can analyze vast amounts of data from DERs and make intelligent decisions in real-time. This enables grid operators to optimize energy distribution, predict demand, and dynamically adjust resources to ensure scalability and flexibility.

Table 6
Potential technologies of 6G for improving SEGM.

Technique	Real-time Monitoring	Fast Data Transmission	Cybersecurity	scalability and flexibility
THz spectrum		✓		
Massive MIMO		✓		
OWC and VLC		✓		
Network slicing		✓	✓	✓
DSA		✓		✓
Edge computing	✓	✓		
AI and ML	✓			✓
Intelligent sensing and IoT	✓			✓
VR/AR	✓			✓
blockchain and cybertwin			✓	✓

7. Conclusion

The potential of 6G wireless networks in SEGM is immense and promising. This review paper has highlighted the vision and potential techniques that can be leveraged to maximize the benefits of 6G technology in smart energy grids. The subsequent points encapsulate the primary key technologies associated with 6G networks and their potential impacts on enhancing SEGM, supported by performance metrics, comparative analysis, or empirical data that have demonstrated the effectiveness of these technologies in addressing critical challenges encountered of smart energy grids.

- Real-time monitoring: Efficient operations in smart energy grids necessitate real-time monitoring capabilities. These capabilities are facilitated by various technologies such as THz spectrum, Massive MIMO, OWC, and VLC.
- Fast data transmission: Vital for managing substantial data volumes generated within smart energy grids, technologies like network slicing, DSA, and edge computing assume pivotal roles in enabling swift and efficient data transmission.
- Cybersecurity: Safeguarding the integrity of data and systems within smart grids is crucial. Technologies such as network slicing, DSA, edge computing, BC, and cybertwin significantly contribute to enhancing cybersecurity measures within the grid infrastructure.
- Scalability and Flexibility: Enabling adaptive and responsive grid management, technologies including network slicing, DSA, edge computing, AI and ML, intelligent sensing and IoT, VR/AR, and BC are identified for their roles in facilitating scalability and flexibility.

The integration of 6G networks presents unparalleled opportunities to tackle challenges conventional energy grids face, including the variability of renewable sources, scalability issues, and cybersecurity concerns. Leveraging the strengths of 6G wireless networks can render energy grids more resilient, reliable, and sustainable. However, the successful deployment of 6G technology in SEGM necessitates addressing infrastructure development, regulatory frameworks, and standardization challenges.

CRediT authorship contribution statement

Jahid Abu: Resources, Investigation. **Alsharif Mohammed H.:** Writing – original draft, Methodology, Formal analysis. **Kim Mun-Kyeom:** Writing – review & editing, Funding acquisition. **Kannadasan Raju:** Supervision, Data curation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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