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Review article

Metaverse-driven smart grid architecture

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ABSTRACT

The power system has experienced significant changes due to digitalization, decarbonization, and decentralization, leading to the emergence of the smart grid concept. Metaverse is a virtual realm that improves the efficiency and cost of smart power system operation and development in various ways that are rarely considered in the literature. This paper aims to integrate the metaverse into the smart grid architecture model and explain its various applications through different use cases. It also examines the challenges and issues related to the metaverse deployment within the smart grid.

1. Introduction

1.1. Background

The three-dimensional revolution of the power system, encompassing decarbonization, decentralization, and digitalization, is elucidated through the Internet of things (IoT) technologies, artificial intelligence (AI)-driven solutions, and renewable energy sources (RES) contributions (Wang et al., 2023). Traditional power grids involve generation, transmission, and distribution entities that hierarchically supply consumers and are centrally controlled by a central control system generally called the supervisory control and data acquisition (SCADA) system (Tightiz and Yang, 2020). Along with the evolution of bulk power generation to distributed generation by RES's advent to decarbonization, the direction and central control of power systems were revolutionized by the Internet and digital communication services. In the current enhanced power system, consumers can play the role of producers by getting access to surplus power generation from RES and communicating with the power system. This interconnected environment includes a two-way stream of electricity and data known as the smart grid. This three-dimensional transformation has enough potential for further enhancement by technologies like virtual reality (VR), Web 3.0, 5G/6G, and digital twin, ultimately synergizing under the metaverse paradigm to validate the cost-effectiveness and efficiency of the entire system (Sun et al., 2022a).

The metaverse is a digital world with a distinct value and a unique economic system closely connected to the real world. The term "Snow Crash" was first introduced by Neal Stephenson in his 1992 science fiction novel (Dwivedi et al., 2022). Users enter and interact with this virtual environment through digital avatars and VR equipment. Philip Rosedale and his colleagues designed the first virtual realm in 2003 called Second Life. As time has passed, the concept has taken on various forms, known as 3D virtual environments and life-logging. This trend intensified in 2021 when Facebook named itself Meta, and COVID-19 transferred whole human social activities to the virtual world. Therefore, metaverse utilization and application have received considerable scholarly attention recently. The number of publications in this area rocketed from 23 to over 200 during the last two years (Sun et al., 2022b). Scholars explored different aspects of the metaverse, including metaverse fundamentals, specifications, architecture, privacy issues, and technology deployment, such as IoT (Li et al., 2022), AI (Huynh-The et al., 2023), and digital twin (Huynh et al., 2022). Furthermore, some researchers focused on investigating a specific metaverse application, such as smart cities (Yaqoob et al., 2023). However, investigation into metaverse applications in smart grid is almost neglected, while they can improve services and emergency response by replicating smart grid operations.

This study aims to fill this gap in the literature by addressing the following research question: How can integrating the metaverse enhance the effectiveness, resilience, and sustainability of the smart grid? This research question guides our investigation into the possible advantages and difficulties of integrating metaverse technology into smart grid systems.

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1.2. Related work

Recent research has investigated multiple aspects of incorporating metaverse technologies into energy systems. Moniruzzaman et al. (2022) investigated energy market platforms as bridging the gap between the physical and digital worlds, enabling prosumers to participate in collaborative immersive activities. With the same approach, Abou El Houda and Brik (2023) examined how to develop effective and open energy markets in the metaverse using blockchain and digital twin technology. The authors in this paper proposed Next-Power, a system for exchanging energy in this virtual environment that is safe and sustainable. Access token-based authentication, automated fair energy payments using blockchain, and a cooperative reputation system for consumers and prosumers are all components of Next-Power.

Maksimović et al. (2023) presented the idea of the energy metaverse to track the consequences of any alterations to the energy environment. This phenomenon enables data exchange between metering, sensors, and actuators as physical objects and guidelines, rules, and business models as unseen assets. Sun et al. (2022a) studied the unique features of the metaverse within the energy internet, highlighting its differences from Web 2.0 and digital twin systems. The authors introduced crucial technologies such as VR, AI, blockchain, and digital twin to enable the metaverse. Moreover, the authors have identified six possible metaverse applications in the energy internet, including monitoring, management, maintenance, the electricity market, virtual power plants, and training. Deng et al. (2022) suggested utilizing the metaverse concept, digital twin, IoT, and cutting-edge communication technology to generate virtual duplicates of energy storage power stations. This schema enables real-time monitoring, detects faults accurately, tracks locations precisely, and sends early notifications to prevent major issues, resulting in smooth operations and reduced expenses. In their investigation of the metaverse's interaction with power systems, Zhou et al. (2023a) highlighted the cutting-edge effects of digital twin and IoT in this area. The authors in this paper examined the metaverse as a tool for immediate observation and improvement of power infrastructures since obtaining instant data on asset functionality allows for better decisions, proactive maintenance, and increased grid productivity by forming digital replicas of tangible assets. However, the metaverse applications in the smart grid are not limited to these small areas.

Technologies that enable the metaverse include the implementation of real-time communication infrastructure (5G/6G), geographic information systems (GIS) for the administration of electrical grid data, AI techniques for analysis and prediction, and the IoT and blockchain for secure decentralization of already-attached power systems to establish the smart grid (Khalid et al., 2023). Zhao et al. (2023) extensively evaluated several cutting-edge technologies, such as blockchain, AI, quantum computing, sophisticated communication systems, and the metaverse, to facilitate the shift to RES and improve smart energy systems. Their research highlights how these technologies can improve energy system efficiency and decentralization in scenarios with high penetration of RES. While the study covers a wide range of technologies and their advantages, it leaves out specific metaverse applications in the energy sector, which is an area that needs more research. Additionally, it lacks a thorough framework for implementing these technologies in energy systems. With the same light of thought, Quan et al. (2022) explored how blockchain, IoT, and metaverse technology might be integrated to improve the administration and functionality of digital power grids. They show how these technologies aid in designing distributed trading schemes and planning multi-source energy scenarios, effectively lowering operating costs and improving grid management.

While many investigations have examined the metaverse potential in various domains, some research has focused on creating frameworks specifically designed for metaverse applications in the power system industry. An inventive metaverse framework that incorporates swarm intelligence to optimize energy scheduling in the energy Internet of things (EIoT) was proposed by Han et al. (2023). The authors of this paper designed a framework for utilizing data-driven intelligence for more efficient energy management. The authors in this framework identified three core components: the scheduling decision-maker, situation awareness, and the system simulator. A distribution grid fault monitoring case study was used to illustrate this framework's efficacy and highlight its applicability in actual situations. A metaverse-based visual simulation model designed for utilization in a power information communication room has been created by Chen et al. (2023). In addition to supporting intelligent inspections and operational training, this model allows for real-time monitoring of the status of power equipment and efficiently represents the spatial relationships between various devices within the space. Additionally, it makes it easier to gather and process a variety of data, such as sensor data and the operational condition of equipment. While the authors' main focus was on differentiating between digital twin and metaverse applications, they did not include a visual depiction of their concept, which would improve comprehension of its advantages and execution. Within the Smart Grid 3.0 paradigm, Adnan (2024) provide a novel convergence framework that combines blockchain, metaverse, and digital twin technologies. The authors in this paper underscore the crucial need for accurate mathematical models to effectively manage and improve these integrations, addressing specific challenges through dynamic and reconfigurable models tailored to immediate grid disruptions. Singh et al. (2022) offered a thorough analysis of digital technology at every step of production, distribution, and energy use. In this study, the authors provided specific suggestions for future improvements in the energy industry, like green IoT creation and the modeling of the smart grid using digital twin.

The goals of our study are thoroughly compared with the other relevant studies' objectives in Table 1. The table highlights how our paper deviates from previous research by addressing two critical issues: "Upgrading Smart Grid Architecture Model" and "Metaverse-Based Smart Grid Framework". Enhancing and altering the current smart grid architecture to improve its functionality, efficiency, and integration with cutting-edge technology is the primary goal of the first aspect, upgrading the smart grid architecture model (SGAM). This involves technical advancements in the grid's structural design, communication protocols, and integration with blockchain, AI, and the IoT to maximize resilience and performance. The second component, the metaverse-based smart grid framework, focuses on the management, user interaction, and simulation of the smart grid within the metaverse by utilizing VR and augmented reality (AR). It includes using metaverse technology to create digital twin, virtual environments, and frameworks for real-time smart grid optimization, control, and monitoring. We aim to improve operational efficiency and user engagement by merging virtual worlds with real-world grid operations. By addressing these two issues, our study sets itself apart from previous relevant research by offering noteworthy architectural innovations and cutting-edge frameworks incorporating metaverse technology into smart grid operations.

Additionally, we carried out a bibliometric analysis of keywords from recent papers included in the Web of Science database to better comprehend the state of the field and highlight any shortcomings in knowledge. Fig. 1 depicts these keywords network, emphasizing notable clusters and their linkages. The most noticeable cluster, highlighted in red, stands for "smart grid" technologies and includes significant terms like "smart meter", "power consumption", and "smart grid technology". The emphasis on energy distribution and management systems in research is highlighted by this cluster. Next to this, the 'digital twin' cluster (shown in green) contains critical terms such as "digital twin model", "case study", and "healthcare". This emphasizes the wide range of applications for digital twin, from industrial settings to healthcare systems, and displays how they can improve our comprehension and modeling of intricate systems. The blue-colored "blockchain" cluster contains phrases like "smart contract", "blockchain technology", and "security analysis". This cluster indicates a rising integration of blockchain with digital twin and smart grid technologies, emphasizing blockchain's critical role in guaranteeing the security and decentralization of data inside the smart grid. A growing cluster marked "metaverse" is also identified in the graphic; it is highlighted in light green and has notable intersections with the blockchain and digital twin clusters. This intersection points to new directions in research, namely in improving virtual representations and interactions within smart systems, where both technologies converge. This bibliometric analysis indicates a significant research gap: although digital twin and smart grid have been thoroughly researched in their fields, there has been comparatively little thorough research on how these technologies interact with metaverse technologies. Although it has not been extensively studied, integrating these cutting-edge technologies holds great potential for improving virtual representation and system interactivity. Our study fills this gap by providing a solid foundation for integrating metaverse technologies into the smart grid architecture model (SGAM). This framework stimulates inventive progress and enables more profound integration among these essential technological spheres.

1.3. Methodology

Embracing cutting-edge digital technology, including the metaverse, brings opportunities and challenges to the energy sector as it continues evolving. In this study, we utilize a conceptual framework based on the phases of digital transformation in energy systems—adoption and adaptation (explained in Section 2), advanced integration (described in Section 3), and optimization (examined in Section 4)—to methodically investigate the metaverse incorporation into smart grid infrastructures. This paradigm will direct our investigation and clarify how incremental integration of digital innovations might improve sustainability and operational efficiency in the smart grid.

In this paper, we adapt the metaverse applications in the power system to the SGAM, which describes the current platform and potential data exchange processes among multiple parties. Adaptation consists of modifying these technologies to meet certain operational requirements and legal limitations, improving their interoperability and usefulness on the smart grid. We investigate the full-scale integration of these technologies into continuing operations in the advanced integration stage to enhance operational functionality and resilience as they become more adapted. The continual improvement of these integrated technologies is the main emphasis of the last stage, optimization. This phase aims to continuously improve technology deployment and operational processes to maximize system performance and handle new difficulties. With the help of this methodical technique depicted in Fig. 2, we can investigate the revolutionary possibilities of metaverse technologies for improving the resilience, sustainability, and efficiency of smart grid systems.

1.4. Contributions

Therefore, the contribution of the paper is as follows:

- Harmonize the SGAM with the metaverse presence,
- Investigate metaverse applications in the smart grid,
- Evaluation of different use cases of the metaverse in the smart grid,
- Study on metaverse deployment in the smart grid challenges and issues.

The remainder of the paper is structured as follows. The concept of the metaverse and its possible application in the SGAM are explained in Section 2. Section 3 highlights various metaverse applications in the smart grid and provides different use cases. The paper concludes in Section 5 after discussing the challenges and obstacles of implementing the metaverse in the smart grid in Section 4.

2. Metaverse in smart grid architecture stage

The smart grid is an innovative solution for the challenges faced by traditional power networks in the rapidly growing energy and technology sectors. It allows power system stakeholders to coordinate seamlessly through automated control and monitoring. This intelligent grid objective is to provide a sustainable, economic, fault-resistant, and cyber-secure process of delivering energy. The stakeholders of this sophisticated grid include conventional or distributed generation units, consumers, and prosumers, who can act as both consumers and generators. As the convergence of the smart grid and emerging technologies becomes more pronounced, the metaverse stands as a pivotal tool in redefining and enhancing power systems. The metaverse is a vast, interconnected digital universe with many different 3D and AR virtual places. These spaces can be utilized for work, play, socializing, and education. The metaverse affects much more than just interaction with others and entertainment. Its immersive and interconnected nature has the potential to transform how we manage and optimize energy systems, especially smart power grids. It is essential to initially acknowledge the metaverse's role within the smart grid framework to fully harness its potential as a catalyst for achieving smart grid objectives in the power system.

2.1. Enhanced SGAM framework with metaverse integration

There are three commonly used models for the smart grid: the National Institute of Standards and Technology (NIST) (Gopstein et al., 2021), IEEE 2030 (Anon, 2013), and the SGAM (Anon, 2012). These models help ensure that smart grid technologies are developed and deployed compatible, secure, and efficient. The NIST smart grid framework is a well-known and complete model for developing and implementing smart grid systems in the United States. It covers communication networks, measurement, and grid operations while allowing consumers access and control. The IEEE 2030 Standard focuses on IoT interoperability with electric utilities and defines communication protocols and data models for the smart grid. It prioritizes security and scalability to integrate IoT into the smart grid. SGAM is a 3-D model that supports smart grid use cases and services mapping. It was created due to the EU Mandate M/490 effort while prioritizing interoperability. SGAM outlines interoperability in the five layers: business layer, function layer, information layer, communication layer, and component layer. The function layer specifies functions and services, while the business layer maps regulations and economic structures of business actors. The communication layer describes protocols for transferring information objects provided by the information layer data models. The component layer includes all power system equipment and information and communication technology devices. This layer categorizes smart grid components based on their zone and domain in conjunction with the smart grid plane (Panda and Das, 2021).

Although a standard architecture model for the metaverse is yet to be accepted universally due to the concept's ever-evolving nature, foundational principles and shared components have captured the attention of both academic and industry circles (Wu et al., 2023). These core principles are interoperability, persistence, scalability, user agency, and an economic system that establishes a virtual economy with trade, property rights, and the potential for a unique currency. Along with these guiding principles, metaverse architectures commonly include virtual environments, avatars, assets, platforms, protocols, and application program interfaces (API). Virtual environments encompass 3D spaces where users engage, ranging from lifelike settings to imaginative realms. Avatars are digital representations of users in various forms, allowing for personalized expressions. Assets are digital objects, tools, or items within the metaverse that users can own, trade, or employ. Platforms are responsible for hosting and operating virtual environments as the foundational systems or services. Protocols are rules governing interactions within the metaverse, ensuring consistency

Table 1
Comparison of related work aspects with the current study on utilization of metaverse in power systems.

Papers	Main objective	Integration of metaverse	Application of AI	IoT applications	Use of blockchain	Deployment of digital twin	Challenges in metaverse integration	Security and privacy	Experimental results	Upgrading the smart grid architecture model	Metaverse-based smart grid framework
Moniruzzaman et al. (2022)	P2P energy trading with metaverse and blockchain	✓	×	×	✓	✓	×	✓	×	×	×
Abou El Houda and Brik (2023)	P2P energy trading with metaverse and blockchain	✓	×	×	✓	✓	×	✓	✓	×	✓
Maksimović et al. (2023)	Metaverse applications in power system	✓	×	×	×	×	✓	×	×	×	×
Sun et al. (2022a)	Metaverse applications in power system	✓	✓	×	✓	✓	✓	✓	×	×	×
Deng et al. (2022)	Metaverse for ESS management	✓	✓	✓	×	×	×	×	✓	×	×
Zhou et al. (2023a)	Metaverse applications in power system	✓	✓	✓	✓	✓	✓	×	×	×	✓
Zhao et al. (2023)	Identification of technology requirements for RES integration	✓	✓	✓	✓	✓	✓	×	×	×	×
Quan et al. (2022)	Metaverse applications in power system	✓	×	✓	✓	✓	×	×	✓	×	×
Han et al. (2023)	Metaverse-based EMS	✓	×	×	×	✓	✓	×	✓	×	✓
Chen et al. (2023)	Metaverse applications in power system	✓	×	×	×	✓	✓	×	×	×	×
Adnan (2024)	Metaverse, blockchain, and digital twin integration to the smart grid	✓	×	×	✓	✓	✓	✓	✓	×	✓
Singh et al. (2022)	IoT, AI, and digital twin integration to the smart grid	✓	✓	✓	✓	✓	✓	✓	×	×	×
Present Paper	Integrating metaverse with the smart grid	✓	×	×	×	✓	✓	×	×	✓	✓

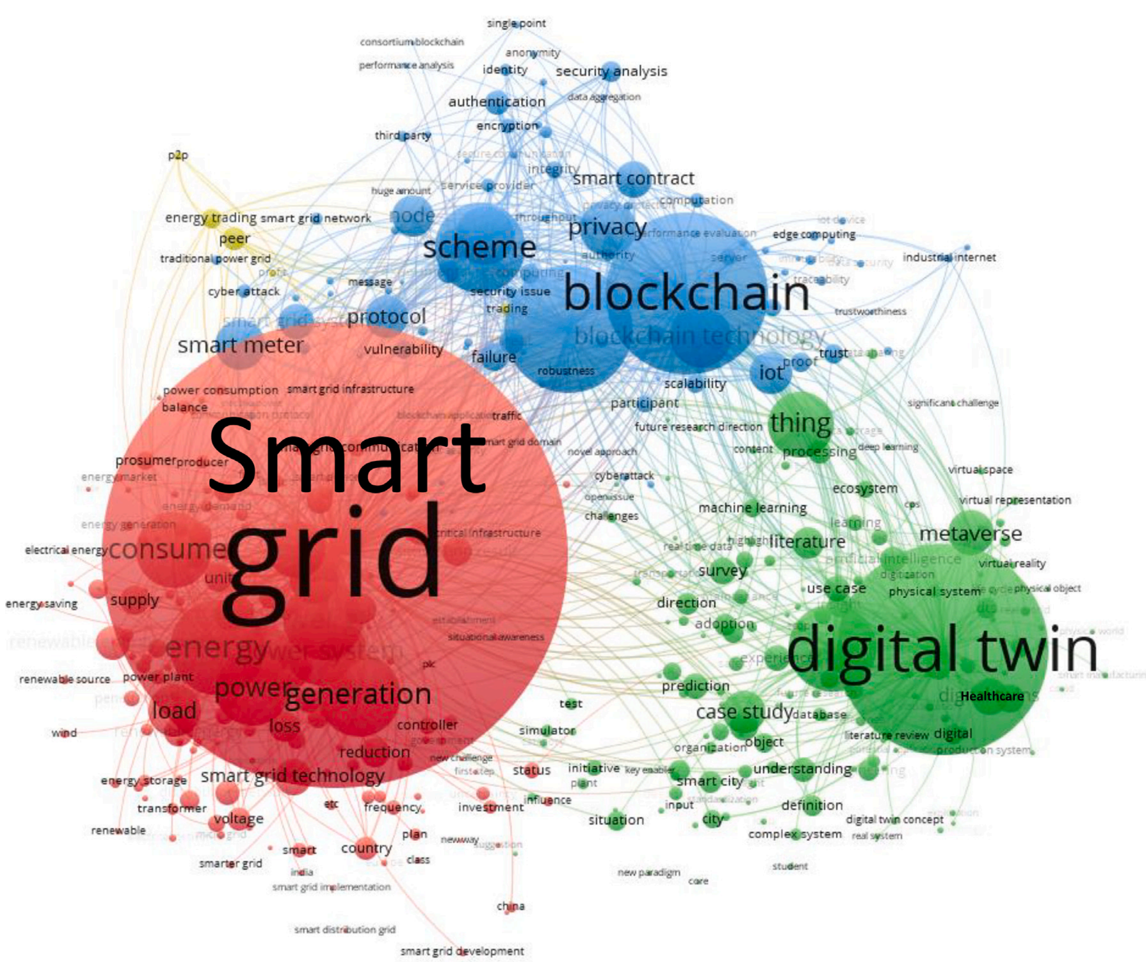

Fig. 1. Bibliographic network of keywords associated with the metaverse, smart grid, blockchain, and digital twin.

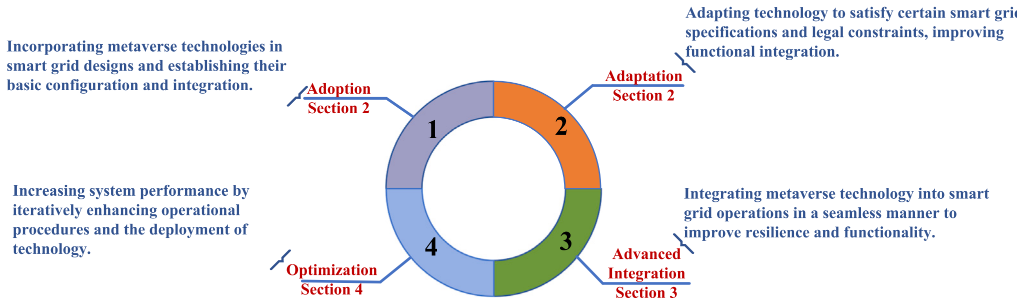

Fig. 2. Our sequential approach for research on metaverse deployment in smart grid systems, with corresponding sections for each phase.

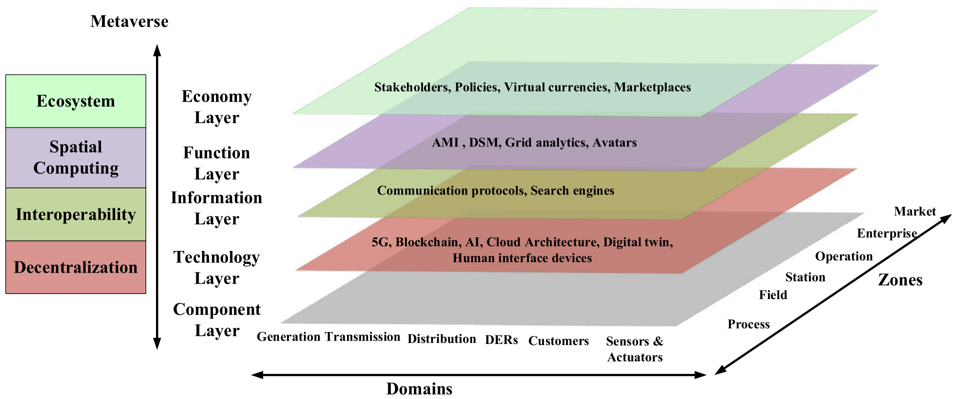

Fig. 3. SGAM with the metaverse presence.

Table 2
Mutual interests between metaverse architecture and smart grid architecture models.

Features/Models	Metaverse	NIST	IEEE 2030	SGAM
Interoperability	✓	✓	✓	✓
Decentralization	✓			
VR & AR	✓			
Digital Economy	✓			
Security & Identity	✓	✓	✓	✓
Integration	✓	✓	✓	✓
Cybersecurity	✓	✓		
Standards Identification		✓	✓	✓
Testing and Certification		✓		
Functional Performance			✓	
Layered Approach	✓			✓

and coherence. APIs are interfaces that permit third-party developers to craft metaverse applications and tools, fostering innovation and expansion (Far and Rad, 2022; Won et al., 2021).

Table 2 highlights the mutual interests between the metaverse architecture model and the three smart grid architecture models. While the metaverse primarily focuses on virtual experiences and digital content, there are areas of common interest, such as interoperability, security, communication, and data management, where insights from one domain can potentially benefit the other. In this paper, we analyze the role of the metaverse in power systems using the SGAM architecture. Fig. 3 displays the SGAM architecture with its metaverse technology presence.

2.2. Identifying modifications to traditional SGAM layers to integrate metaverse

This section explores the revolutionary improvements made to the conventional SGAM layers, building on the fundamental integration of metaverse technologies with the SGAM, as described in the previous section. These improvements are essential for improving the data flow dynamics and operational efficiencies across the SGAM, as Fig. 4 clearly illustrates.

Blockchain technology is shown in Fig. 4 as a key element integrated into the cloud data center, improving data integrity and offering a safe network for communication throughout the smart grid. Blockchain technology guarantees that all interactions are transparent and unchangeable by generating a decentralized ledger that immutably records every transaction. Making it easier for decentralized data to be shared in real-time, which is essential for dynamic grid management, improves security while fostering confidence among grid members.

IoT and AI-enhanced sensors make large-scale data collection and real-time processing from the virtual and physical worlds possible. The diagram's incorporation of 5G/6G technologies highlights their significance in guaranteeing incredibly swift and dependable data transmissions, which are crucial for facilitating real-time analytics that propel operational decision-making and agility in the smart grid.

Introducing cryptocurrencies into the SGAM facilitates financial transactions within the smart grid. These virtual currencies, supported by blockchain technology, make financial transactions more secure, transparent, and traceable. By removing conventional banking middlemen, this integration not only streamlines transactions but also has the potential to completely transform the energy market's economic landscape.

The SGAM has undergone revisions incorporating metaverse technologies to make the grid more reliable, secure, and effective. Great details about how these technologies are used in the smart grid, highlighting particular use cases and the revolutionary effects they enable, are discussed in Section 3.

3. Metaverse applications and use cases in smart grid

The potential uses of the metaverse in conjunction with the layers of the SGAM in the energy and utilities sector are discussed in this section. We can realize the full potential of these two areas' convergence by integrating them to foster innovation, smarter operations, and broader stakeholder participation.

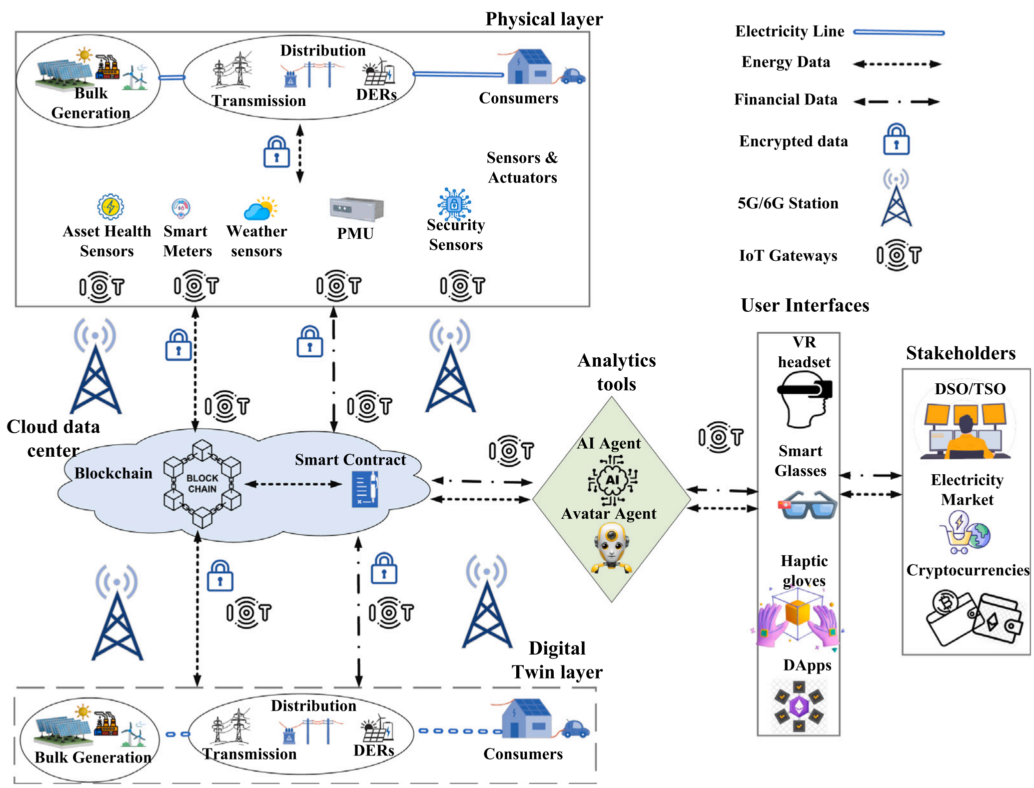

Fig. 4. Data flow and operational enhancements in the metaverse-integrated SGAM.

3.1. Economy layer

3.1.1. Decision-making and strategic planning

Virtual grid modeling entails building precise virtual representations of the smart grid in the metaverse to track and simulate grid behaviors in real-time. Electrical faults are a recurring challenge within power system networks, and they can manifest for multiple reasons, including lightning strikes, equipment malfunctions, and environmental factors. These disturbances invariably lead to high fault currents, regardless of the specific trigger. The security of the power system is of utmost importance and requires prompt identification and rectification of faults. Modern technology integration, such as wide area monitoring systems (WAMS) and phasor measurement units (PMU), has facilitated the development of protection schemes to preserve the power system's integrity. These schemes, called system integration protection schemas (SIPS), oversee the entire network and take essential measures to avoid system-wide outages (Tightiz and Yang, 2021). The metaverse comes into play as a powerful tool in executing SIPS. It enables strategic planning and decision-making in a virtual environment, where simulations can be conducted to assess the impact of various protection measures on the power system's overall integrity. By harnessing the metaverse's capabilities, power system operators and engineers can conduct advanced analyses, explore different scenarios, and optimize the response to potential faults or disturbances, ultimately enhancing the resilience and reliability of the power grid. Disaster response simulations are another approach to training staff on best practices by simulating grid reactions to natural disasters or other events (Khanal et al., 2022).

Using digital twin and the metaverse, Enel Grids' GridVerse project improves grid management and cooperation with a ground-breaking strategy. Creating a virtual environment allows assets to be represented and interacted with, improving operational safety and efficiency. GridVerse's open protocol foundation demonstrates a step forward in the digital evolution of the smart grid by providing broad interoperability and chances for collaboration amongst diverse stakeholders (Jones, 2024).

3.1.2. Involving stakeholders and fostering public consciousness

The metaverse provides new opportunities for stakeholders such as utilities, regulators, research institutions, and standard organizations to collaborate and raise public awareness. This involves organizing virtual stakeholder meetings in immersive metaverse environments and facilitating dynamic discussions on grid-related developments, challenges, and potential solutions. At the same time, the metaverse can be used as an educational tool to offer virtual tours of the smart grid's complex infrastructure to the public, students, and researchers. These tours help promote understanding and awareness, transcending geographical barriers and making knowledge dissemination more accessible. A comprehensive simulator called Smart Grid MR 2.0 can replicate many aspects of how electrical grids work, including energy production, distribution, storage, and consumption. In this virtual game, a player controls an electric vehicle (EV), with real-world interactions with up to 15 other players influencing their experience. These real-world actions, such as generating energy, directly affect the virtual realm by powering EV charging stations (Franco et al., 2023).

3.2. Function layer

3.2.1. Grid optimization and load balancing

Grid optimization and load balancing are essential for maintaining grid stability and preventing blackouts. The metaverse provides a platform for running advanced simulations that help operators understand the impact of different load profiles, renewable energy inputs, and grid adjustments. Operators can fine-tune load-balancing strategies, optimize grid performance, and allocate resources by experimenting within this virtual realm. Engineers and designers who are involved in developing new grid components or systems can benefit from collaborative design spaces within the metaverse. These virtual environments allow teams to work together to design and test new concepts, regardless of their physical locations. Create 3D models, conduct simulations, and evaluate the feasibility of innovative grid technologies before investing in physical prototypes available with metaverse deployment. This cooperative method expedites the design and development of power systems while lowering costs and resource usage.

The TalTech Campulse Project (Zhou et al., 2023b) illustrates the application of digital twin technology for microgrid energy management optimization. The project effectively combines big data analytics, machine learning, and IoT to enable peak shaving and boost energy efficiency in real-time operations within regional energy communities. Under Russia's 'Digital Economy' national agenda, an intelligent system was built there to optimize renewable energy sources through the use of digital twin technology (Simankov et al., 2023). Using multi-criteria analysis, this method improves decision-making for effective management of renewable energy.

3.2.2. Virtual power plants (VPP) management

VPPs comprise a network of distributed energy resources (DER). VPP management becomes more efficient and dynamic with the metaverse's contribution. Operators can create virtual representations of these distributed assets, monitor their performance, and simulate various operational scenarios. This enhancement facilitates making decisions in real-time and enables the testing and refinement of control strategies without affecting physical systems (Ali et al., 2022).

3.3. Information layer

3.3.1. Visualizing data and analyzing

Metaverse integration to the smart grid information layer upgrades data visualization and analytics to a new level. Operators and analysts can navigate virtual data landscapes in 3D, which makes it easier to identify patterns and trends in the grid's performance. This immersive approach enhances their understanding and allows for the seamless integration of advanced analytics tools within the metaverse. These tools can process vast datasets in real-time and unlock valuable insights for optimized decision-making, ensuring operators can respond swiftly to grid events.

The idea of virtual control centers is essential for assisting decision-makers in real-time, especially those who oversee power systems. Operators may use the metaverse to access data and controls for different grid components and monitor and operate the smart grid in real-time through 3D virtual environments. With this strategy, power system operators can make better decisions and have a more comprehensive understanding of the state of the grid. It also makes it possible to react to grid events more quickly, which reduces downtime and increases reliability. Field technicians can use AR devices to observe real-time overlays of grid components as part of routine grid maintenance and repair. The AR-enhanced information layer in the smart grid design improves the effectiveness and efficiency of maintenance, repair recommendations, and troubleshooting.

One example of how digital twin technology is used in the information layer of the SGAM framework is the case of Ikaria Island in Greece (Fotopoulou et al., 2023). Through the integration of real-time analytics and advanced data management, this project maximizes the performance of the smart grid, enabling effective simulation, control, and monitoring. The digital twin enhances operational efficiency and decision-making by offering a dynamic, virtual picture of the physical grid through the utilization of continuous data flow from sensors and IoT devices.

3.3.2. Consumer engagement

The interconnection of digital twin related to energy and society creates a digital ecosystem known as the energy metaverse. This interconnectedness enables the creation of online energy marketplaces, where consumers can participate more actively in power grid operations (Ma, 2023). The metaverse provides tools, such as virtual home energy management, that allow homeowners to monitor their energy consumption in a virtual environment. This platform empowers consumers to make informed energy decisions, promotes interactions between energy producers and consumers in both real and virtual spaces, and leads to optimized energy use and cost savings.

3.4. Technology layer

3.4.1. Remote collaborative work and training

Within the field of smart grid, the metaverse offers a potent platform for online training and distant collaboration. Grid operators, technicians, and engineers can connect virtually, regardless of their physical locations, to collaboratively troubleshoot, learn, and share knowledge. Virtual meeting spaces and immersive training modules facilitate hands-on training and knowledge transfer, making it easier for professionals to stay updated on the latest grid technologies and operational procedures (Han et al., 2022).

They 'Urban Futurability' project is a prime example of how technology is being integrated into power utilities in Brazil (João et al., 2020). To improve human interfaces inside electrical distribution networks and increase operational efficiency and safety, this project used VR/AR. Utility employees might engage with intricate grid systems in a safe virtual environment by implementing these technologies, enhancing decision-making and lowering operational hazards. Similar to this, a team that created a VR training game found a useful application for immersive VR in substation operating training (Alonso-Rosa et al., 2020). This game offers operators realistic simulations that improve safety and proficiency. It is built around a comprehensive building information model (BIM) of a 115 kV substation. How the game affects operator engagement and usability shows how VR can revolutionize standard training techniques by improving the safety and intuitiveness of complicated and hazardous environment interactions. VR training system in Xu et al. (2019) provides a safe, interactive platform for technicians to practice and refine their skills without the risks associated with live line work.

3.4.2. Research and innovation

The metaverse presents a groundbreaking platform for researchers and innovators to access state-of-the-art tools and resources, advancing the development of smart grid technologies and energy solutions. Virtual laboratories allow researchers to conduct experiments in virtual environments without requiring physical prototypes. Doing this expedites the research and development process, and the experimentation costs are also significantly decreased. The metaverse also hosts innovation showcases, enabling companies and organizations to use this digital realm to exhibit their latest smart grid technologies and solutions. A global platform is created through virtual expos, fairs, and showcases, allowing engagement with a diverse audience of experts and potential collaborators. This approach, focused on fostering innovation, promotes the exchange of ideas, encourages partnerships, and accelerates the adoption of cutting-edge grid technologies (Franco et al., 2023).

3.5. Component layer

3.5.1. Digital mirror of physical assets

The component layer uses the metaverse extensively by generating virtual twin representations of tangible assets. Grid operators can continuously monitor, analyze, and replicate the behavior of physical resources according to their virtual counterparts. Operators thus acquire a thorough insight into asset performance in real-time. This information empowers data-driven decision-making, leading to optimized operations, predictive maintenance, and enhanced grid efficiency and resilience (Cho et al., 2022). To improve street lighting management in urban environments, asset management was developed by merging IoT, VR, and digital twin technologies, as detailed in Campo et al. (2023).

Furthermore, the metaverse plays a crucial role in security and compliance. Within virtual environments, cybersecurity experts can proactively monitor potential threats to the smart grid and create real-time response strategies. This schema promptly detects and mitigates cyber threats, ultimately reducing the risk of cyberattacks. In addition, regulators leverage the metaverse to conduct virtual audits of the smart

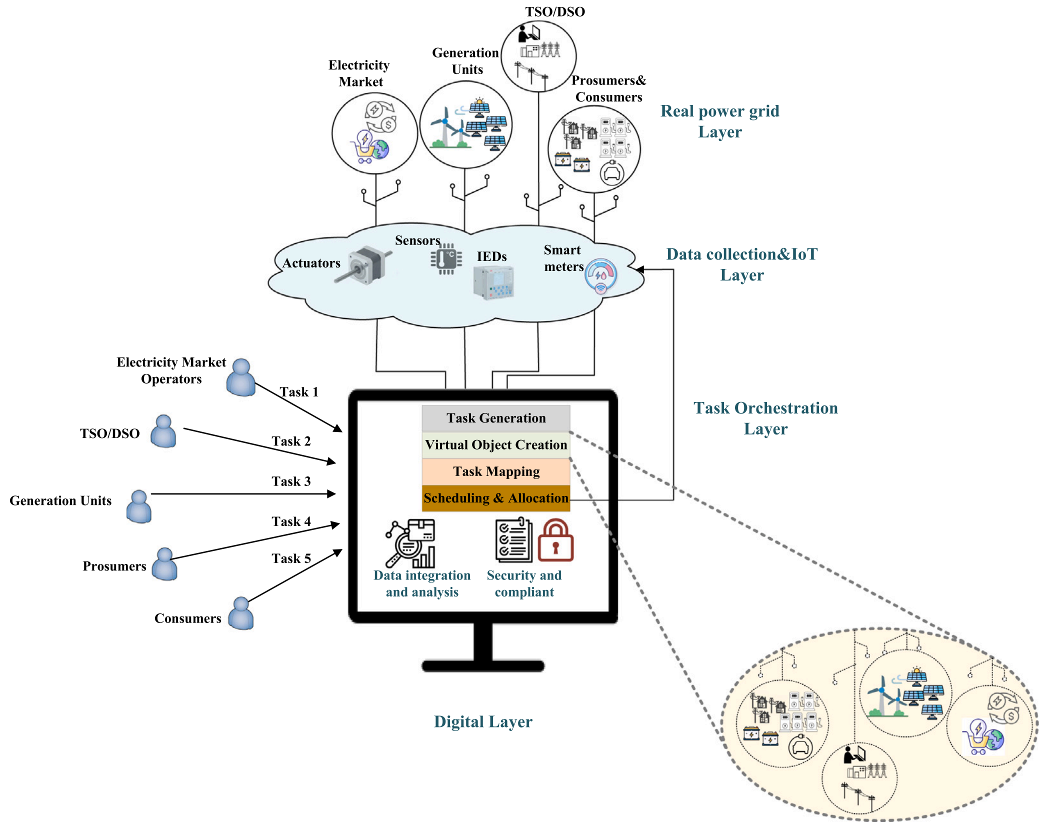

Fig. 5. Digital twin framework for virtualized power systems.

grid infrastructure, ensuring adherence to established standards and regulations. This process offers a streamlined, cost-effective approach to compliance monitoring while preserving the grid's integrity.

Fig. 5 illustrates a framework for virtualizing power systems. In this framework, the IoT layer with sensors, actuators, and intelligent electronic devices (IED) gathers real-time data, receives commands, and communicates with the virtual world. The task orchestration layer follows a sequential process that includes task generation, virtual object creation, task mapping, and task scheduling. It reflects the defined tasks by different power system stakeholders in the virtual world. Information from various sources in real power systems, including the IoT layer and physical infrastructure, should be harmonized and integrated for real-time analysis within the digital twin environment. The virtual power system has a feedback loop from the task orchestration layer to the IoT layer for real-time adjustments and optimized performance. This mechanism is a self-correcting tool to maintain accurate digital representations over time. As power systems become more digitalized and interconnected, they become potential targets for cyber threats. The security role within the framework is to safeguard both physical and virtual systems from these threats (Jaipong et al., 2023).

Fig. 6 maps the several applications discussed in this part to improve grid management and operational efficiency across the SGAM layers. Additionally, Table 3 provides an overview of some real-world applications of metaverse technologies in the smart grid, including the deployed technologies, application domains, and how they fit into the SGAM layers to show their effects and real-world implementations.

4. Obstacles and challenges

Smart grid architectures incorporating the metaverse face particular challenges that need careful examination and measured solutions. The difficulties vary from interoperability problems and infrastructure requirements to moral dilemmas and financial impacts. These difficulties demonstrate the potential for major improvements in grid administration and operation and the hardship of incorporating advanced technologies into legacy systems. Table 4 represents an overview of these issues and their remedies. These issues are covered and analyzed as follows:

4.1. Evolutionary and adaptation requirements

The metaverse concept is still in its initial stage, with ongoing progress in hardware and business exploration. As a result, metaverse applications are still developing and integrating without standard procedures and guidelines. Key enabling technologies like 5G/6G and distributed computing require significant development. Due to limited advancement in 6G technology, such as the absence of broad established infrastructure and primitive technological standards, introducing a metaverse-inspired system for monitoring the electrical grid in real-time can be challenging (Zhang and Liu, 2023).

Considering the constraints of 6G networks, network slicing is an achievable solution. This strategy is crucial for facilitating the integration of metaverse technology into the smart grid. Thanks to network slicing, several virtualized, separate networks can be created on the same physical infrastructure. Every network slice can be configured to match the unique needs of various metaverse applications, providing varying degrees of performance, security, and connectivity. This helps with flexibility and scalability in response to the changing standards and infrastructure requirements of 6G while optimizing resource usage (Zawish et al., 2024).

4.2. Infrastructure and energy-intensive

Massive infrastructures such as data, computing, and communication infrastructures are required to apply the metaverse to the smart grid. With the improvement of user involvement in metaverse-based

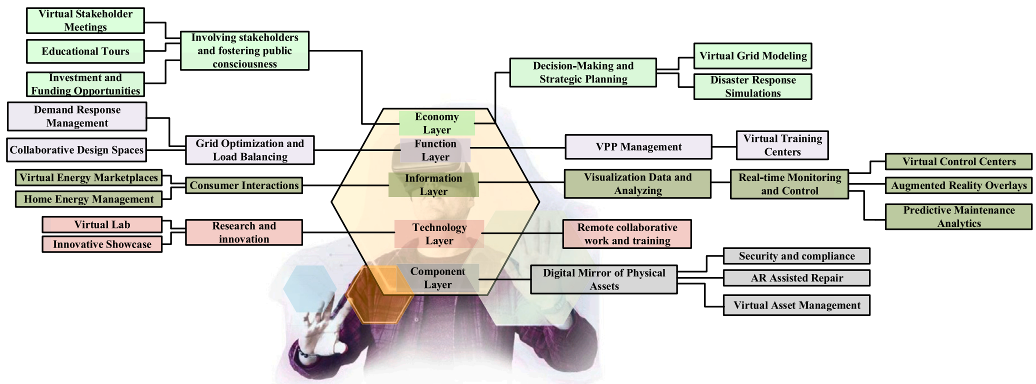

Fig. 6. Metaverse applications in smart grid.

Table 3
Summary of practical projects using metaverse technologies in the smart grid.

Project name	Technology used	SGAM layer	Metaverse application	Contribution description	Ref
Urban Futurability	VR & AR	Technology Layer	Remote Collaborative Work and Training	Utilizes VR/AR for enhancing human interfaces and operational safety, enabling remote training and decision-making support.	João et al. (2020)
		Component Layer	Digital Mirror of Physical Assets	Provides a virtual representation of the grid, enhancing operational efficiency and safety through immersive simulations.	
Smart Grid MR 2.0	VR & AR	Economy Layer	Involving Stakeholders and fostering public consciousness	Engages stakeholders through virtual platforms, facilitating public awareness and education on smart grid technologies.	Franco et al. (2023)
VR-based Operator Training for Substation Maintenance	VR	Technology Layer	AR and VR-based Training	Offers VR-based training for substation operations, improving safety and operational skills.	Alonso-Rosa et al. (2020)
VR-based Live Line Work Training	VR	Technology Layer	AR and VR-based Training	Offers VR-based training for live line workers, improving safety and operational skills.	Xu et al. (2019)
GridVerse	Digital twin & VR	Economy Layer	Decision-making and Strategic Planning	Uses digital twin and VR for virtual grid management, enhancing strategic planning and decision-making capabilities.	Jones (2024)
		Component Layer	Digital Mirror of Physical Assets	Provides a virtual representation of the grid, supporting detailed planning and analysis.	
TalTech Campus Digital Twin	Digital twin & IoT & AI	Function Layer	Grid Optimization and Load Balancing	Integrates digital twin and IoT for efficient energy management and real-time grid optimization.	Zhou et al. (2023b)
		Component Layer	Digital Mirror of Physical Assets	Provides a virtual representation of physical assets for better management and maintenance.	
Digital Twin on Ikaria Island	Digital twin & IoT	Information Layer	Real-time Monitoring	Offers comprehensive monitoring and analytics for enhanced grid management.	Fotopoulou et al. (2023)
Intelligent Analytical System	Digital twin & AI	Function Layer	Grid Optimization	Uses AI and digital twin for real-time data analytics and optimization of renewable energy systems.	Simankov et al. (2023)
Digital Twin for Smart Street Lighting	Digital twin & VR & IoT	Component Layer	Digital Mirror of Physical Assets	Provides virtual representations for predictive maintenance and efficient asset management in urban environments.	Campo et al. (2023)

power systems due to inadequate infrastructure, it will experience system overloads and breakdowns in peak user activities. Additionally, this requirement demands a significant energy supply, which might intensify the contradiction between energy generation and consumption as the metaverse becomes more integrated into the power system. Using MEMS and nanotechnology, self-powered sensors can reduce power usage significantly. These sensors provide long-term, maintenance-free monitoring of power systems for metaverse the smart grid paired with energy-harvesting devices (Fan et al., 2023).

Scalability becomes a significant difficulty when integrating blockchain with metaverse technologies for the smart grid, especially when managing large transactions and real-time processing needed for effective energy trading. The usefulness of blockchain in large-scale, dynamic contexts such as the smart grid may be hampered by its inherent constraints in terms of transaction costs and processing speed. However, new developments described in the study point to adopting blockchain frameworks and unique consensus processes more appropriate for energy-related transactions. Implementing a hybrid blockchain paradigm could solve these scaling problems.

This architecture offers a customized solution that can manage the high transaction volumes typical of peer-to-peer energy trading platforms by merging the security and transparency of public blockchains with the speed and efficiency of private blockchains. Additionally, it is suggested that integrating lightweight consensus protocols – which lower computational costs and boost transaction throughput – is a workable way to improve the scalability of blockchain applications in the smart grid. Blockchain technology must advance to fulfill metaverse-enhanced smart grid ecosystems' large-scale, real-time transaction requirements (Moniruzzaman et al., 2022).

4.3. Ethics and privacy concerns

Metaverse poses significant ethical and privacy issues for the utility grid due to the large amount of private information and commercial data interactions. It is vital to prioritize personal information protection and corporate data protection to ensure the security of consumers and prosumers. However, operating the metaverse on a network of connected nodes and servers results in being complicated to provide privacy (Jaipong et al., 2023). Therefore, collaboration between power grid operators, regulatory agencies, technology developers, and cybersecurity specialists will be necessary. One of the main challenges in this setup is ensuring the security of prosumer data and representing energy as a digital asset in the virtual space. Blockchain technology offers a solution. It allows for creating these digital energy assets and their trade using cryptocurrency within the metaverse. A real-world application of this concept can be seen with the Korea Electric Power Corporation (KEPCO). In the past, KEPCO stored excess energy from prosumers, particularly from rooftop solar panels, at an added cost. They introduced a hybrid peer-to-peer blockchain system to make this process more efficient. This system lets prosumers trade energy among themselves first. Any leftover energy is then sent to KEPCO, reducing storage needs. Using energy tags based on smart contracts also eliminated transaction fees, leading to significant cost savings for both KEPCO and the prosumers. This innovative approach transformed KEPCO from just a power company to an active prosumer in the national grid (An et al., 2022).

4.4. Challenges of integration and interconnection

Current electricity systems combine traditional and smart power systems. The integration of these disparate systems can cause operational inefficiencies and compatibility problems, especially when attempting to integrate cutting-edge metaverse platforms. Power systems with outdated infrastructure could struggle interacting with recently launched metaverse platforms with real-time energy trading, resulting in lost trading opportunities.

4.5. Standardization and interoperability

With the integration of metaverse technologies into power systems, such as IoT systems, blockchain technology, and digital twin, numerous platforms and protocols are accessible. This integration becomes challenging and prone to errors due to the absence of standards and interoperability, which serve as the common language of diverse systems. As an illustration, two nearby prosumer communities might use various metaverse platforms to keep track of their renewable energy supplies. Without established standards and interoperability protocols, they cannot effectively share resources or information.

New efforts have focused on developing uniform frameworks and protocols to address standardization and interoperability issues in integrating metaverse technologies into power systems. The ITU Metaverse Focus Group (FG-MV) emphasizes the importance of developing standard operating procedures for deploying metaverse applications in various fields, including power systems. The FG-MV aims to provide a common language and set of standards to enable the smooth and error-free integration of various metaverse platforms within the power sector by defining use cases for grid and user-side applications (ITU Focus Group on Metaverse (FG-MV), 2023).

4.6. Safety and reliability

The power system is a sensitive infrastructure, and any malfunction or error could have detrimental impacts. Therefore, when integrating the metaverse, it is imperative to ensure that the virtual platform does not compromise the security and reliability of the physical system. For instance, if a metaverse platform incorporates nuclear power plant safety systems, severe issues can appear if the platform gets a defect that results in false safety readings.

When solving the critical problems of guaranteeing security and dependability in the power system infrastructure – especially when incorporating complex metaverse platforms – new approaches like quantum key distribution (QKD) and optical wireless communications (OWC) provide significant improvements. By integrating OWC, the data transmission capabilities required for real-time critical infrastructure monitoring and control are improved, guaranteeing that the high-speed communication requirements of metaverse applications are satisfied without jeopardizing system integrity. Moreover, implementing QKD creates an inherently unbreakable quantum mechanics-based security layer that protects the transfer of critical operational data. Combining these two elements is especially important when metaverse technologies directly interface with vital safety systems, such as those in nuclear power plants, where precise and secure data interchange is necessary to avoid the catastrophic outcomes of incorrect readings or delayed system reactions. The integration of metaverse applications can move forward without endangering the resilience and reliability of the power system's infrastructure by utilizing these cutting-edge technologies (Safari and Kharrati, 2023).

4.7. Financial aspects

Although the metaverse has many benefits, it also has expenses associated with its creation, integration, service, and upgrades. Local utility grids and prosumers with limited financial resources can struggle with the burden of these charges on their budgets.

Integrating avatars into the metaverse for the smart grid has distinct cost obstacles, mainly due to the requirement for advanced, safe, and legally compliant technologies. Leveraging blockchain can offer a cost-effective option for secure data handling and identity management, mitigating high initial expenses and lowering potential legal liability related to privacy breaches. Moreover, expanding user interactions can be effectively handled by using scalable avatar management frameworks without correspondingly rising expenditures. These methods guarantee adherence to strict data privacy regulations and improve the metaverse infrastructure's overall security and economic feasibility in the smart grid (Cheong, 2022).

5. Conclusion

The metaverse integration into the smart grid framework has become possible due to the evolution of power systems. This evolution is characterized by digitalization, decarbonization, and decentralization. In this paper, we have explored the transformative potential of the metaverse in enhancing the efficiency, resilience, and sustainability of the smart grid. We have highlighted various applications, use cases, and challenges associated with this integration by harmonizing the smart grid architecture model with the metaverse. The metaverse can create virtual twins of physical assets, offering a platform for real-time monitoring, decision-making, and optimization of power systems. The metaverse's role in ensuring security, compliance, and proactive threat monitoring underscores its significance in the future of the smart grid. As the convergence of these two domains continues, it promises a future where power systems are more intelligent, responsive, and aligned with the digital era's demands.

Table 4
Challenges and solutions for key metaverse technologies in the smart grid.

Technology/ Equipment	SGAM layer	Role in metaverse integration	Challenges	Proposed solutions
5G/6G stations	Technology layer	High-speed data transmission	Infrastructure costs, and coverage issues	Collaboration with telecommunications providers to utilize existing infrastructures and invest in technology-specific infrastructure developments.
Blockchain	Technology layer	Secure transactions and data management	Scalability and energy consumption	Implement lightweight blockchain technologies and explore hybrid blockchain models for efficiency and scalability.
IoT gateways	Component layer	Connect sensors and devices	Security vulnerabilities and interoperability issues	Develop advanced cryptographic solutions and use standard-based protocols for interoperability.
Digital twin	Information layer	Simulation and analysis of physical assets	High computational demands and integration challenges	Utilize distributed learning for data processing to reduce computational load and enhance data synthesis.
AI agents	Technology layer	Enhance decision-making through predictive analytics	Privacy concerns and algorithmic bias	Integrate ethical AI frameworks to guide development, ensuring fairness and transparency.
Smart contracts	Technology layer	Automate digital agreements	Development complexity and potential bugs	Use smart contract templates and frameworks that have been rigorously tested for reliability and security.
Avatars	Function layer	User representation in the metaverse for interaction	Adherence to data protection regulations, maintenance of user confidentiality, mitigation of identity theft threats, and the substantial expenses of creating safe and ethical avatars	Adopting scalable avatar management systems to cut down on operating expenses, apply GDPR-compliant data handling procedures, and leverage blockchain technology to improve user identity verification and data integrity
PMUs and sensors	Component layer	Monitor grid performance and health	Evolutionary and adaptation requirements	Improve sensor accuracy, employ advanced data management solutions.

CRediT authorship contribution statement

Lilia Tightiz: Writing – review & editing, Writing – original draft, Visualization, Validation, Investigation, Conceptualization. **L. Minh Dang:** Writing – review & editing, Conceptualization. **Sanjeevikumar Padmanaban:** Writing – review & editing, Writing – original draft, Supervision. **Kyeon Hur:** Methodology, Investigation.

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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