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Review

The Role of Smart Grid Technologies in Urban and Sustainable Energy Planning

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Abstract: Traditional centralized energy grids struggle to meet urban areas' increasingly complex energy demands, necessitating the development of more sustainable and resilient energy solutions. Smart microgrids offer a decentralized approach that enhances energy efficiency, facilitates the integration of renewable energy sources, and improves urban resilience. This study follows a systematic review approach, analyzing the literature published in peer-reviewed journals, conference proceedings, and industry reports between 2011 and 2025. The research draws from academic publications of energy institutions alongside regulatory reports, examining actual smart microgrid deployments in San Diego, Barcelona, and Seoul. Additionally, this article provides real-world case studies from New York and London, showcasing successful and unsuccessful smart microgrid deployments. The Brooklyn Microgrid in New York demonstrates peer-to-peer energy trading, while London faces regulations and funding challenges in its decentralized energy systems. The paper also explores economic and policy frameworks such as public–private partnerships (PPPs), localized energy markets, and standardized regulatory models to enable microgrid adoption at scale. While PPPs provide financial and infrastructural support for microgrid deployment, they also introduce stakeholder alignment and regulatory compliance complexities. Countries like Germany and India have successfully used PPPs for smart microgrid development, leveraging low-interest loans, government incentives, and regulatory mechanisms to encourage innovation and adoption of smart microgrid technologies. In addition, the review examines new trends like the utilization of AI and quantum computing to optimize energy, peer-to-peer energy trading, and climate resilient design before outlining a future research agenda focused on cybersecurity, decarbonization, and the inclusion of new technology. Contributions include the development of a modular and scalable microgrid framework, innovative hybrid storage systems, and a performance-based policy model suited to the urban environment. These contributions help to fill the gap between what is possible today and what is needed for future sustainable urban energy systems and create the foundation for resilient cities of the next century.

Keywords: smart microgrids; sustainable energy planning; artificial intelligence; urbanization; energy; distributed energy resources

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1. Introduction

As urbanization increases more than expected, 68% of the world's population will live in cities in 2050 [1]. This growth puts enormous pressure on existing energy systems, which are often centralized, outdated, and unprepared to deal with the increasing complexity of urban energy demands. However, the current grids are inadequate to support sustainable urban development in the global push for renewable energy and greenhouse gas reduction. Consequently, smart microgrids have come up as a solution to these conundrums [2,3]. Within decentralized energy systems, distributed energy resources (DERs), advanced storage technologies, and intelligent management systems are integrated into localized systems to achieve local high efficiency and resilience [4]. Unlike traditional grids, smart microgrids present a new framework to meet fluctuating energy demands, integrating renewables and expanding urban spaces' boundaries. However, large technical, economic, and policy barriers exist to their large-scale deployment and rethinking of how the energy system is planned and implemented [4,5].

Previous research has thoroughly studied DER integration, storage technologies, and real-time monitoring systems yet fails to bridge the necessary connection between these technologies with urban sustainability and resilience frameworks. Advanced control systems affecting microgrid efficiency served as the primary topic in research by Almihat and Munda [6] without considering urban sustainability effects. EMS implementation using artificial intelligence was analyzed by Arévalo et al. [7] without a review of market affordability or regulatory constraints. This review fills the knowledge gaps by integrating technological progress with its policy framework effects, economic dimensions, and resilience performance. The review integrates findings on AI, blockchain, and predictive analytics, illustrating their transformative potential in future energy management systems. For instance, Almihat and Munda [6] study the effect of advanced control systems on microgrid efficiency enhancement, and Arévalo et al. [7] consider using an artificial intelligence (AI)-based energy management system (EMS) to enhance energy utilization. These studies are instructive but rarely consider integrated urban sustainability, policy fit, and economic viability. Further, current research on microgrid technology overlooks the need for innovations to prolong their usefulness. Integration with emerging technologies such as nanotechnology-based materials, wireless power transfer systems, and hybrid storage solutions is underexplored [8]. Additionally, minimal attention is given to how policy frameworks and economic models can enable the scalability and resilience of urban microgrids as they adapt to developing urban environments and changing climate conditions [9].

However, this review addresses these gaps by thoroughly analyzing smart microgrids' role in urban and sustainable energy planning, especially regarding long-term sustainability and resilience. These include AI, quantum computing, hybrid energy storage, and adaptive architectures for improving the performance and longevity of urban microgrids [7,10,11]. This review discusses these aspects. It discusses economic and policy approaches to public–private partnerships (PPPs), localized energy markets, and performance-based incentives. It also enables future-proof solutions like predictive planning models and new technologies to keep the 21st century smart microgrids. This review highlights the need for modular designs, advanced materials, and self-healing systems to enable resilience and disaster recovery. This review, therefore, addresses these dimensions to provide a roadmap for advancing smart microgrids as a cornerstone of urban energy systems. Nevertheless, the main purpose of this review is to provide a forward-looking view toward supporting the appearance in the emerging frontiers of smart microgrid literature. This review proposes innovative solutions and showcases best practices so policymakers, researchers, and industry leaders can speed up smart microgrid deployment in urban areas, leading to a more sustainable and resilient energy future.

This review makes several key contributions to smart microgrid technologies and urban energy planning. While existing studies provide fragmented insights into smart microgrid development, this review synthesizes these insights into a cohesive framework tailored for urban energy systems. Unlike previous research, this study introduces a modular microgrid architecture that adapts to varying urban conditions, incorporates AI-enhanced energy forecasting, and proposes a hybrid energy storage model that optimizes efficiency. Furthermore, it uniquely examines the regulatory and financial mechanisms essential for large-scale microgrid deployment. First, it presents a systematic and forward-looking analysis of how emerging technologies, such as AI and quantum computing, can optimize urban microgrid operations. Second, it evaluates economic and policy frameworks, including PPPs and localized energy markets, identifying best practices for scalable deployment. Third, it introduces a novel approach to hybrid energy storage that integrates solid-state batteries, hydrogen fuel cells, and flow batteries, providing a sustainable energy storage solution tailored to urban microgrids. Finally, the review identifies future research directions, particularly cybersecurity, decentralized energy trading, and urban resilience planning.

This study follows a systematic review approach, analyzing the literature published in peer-reviewed journals, conference proceedings, and industry reports between 2011 and 2025. The selection criteria included relevance to smart microgrid technologies, urban energy planning, and sustainability. A keyword-based search strategy was employed using terms such as 'smart microgrids', 'urban energy resilience', 'AI in microgrid management', and 'renewable integration in urban settings'. The review encompasses the literature from leading energy research institutions, regulatory agencies, and case studies of implemented smart microgrids in cities such as San Diego, Barcelona, and Seoul. The findings are synthesized into key themes, highlighting technological, economic, and policy-related advancements.

The review is structured into eight sections corresponding to key aspects of smart microgrid technologies and their applications in urban energy planning. In Section 2, a detailed review is conducted on the current state of the art of smart microgrid technologies, including capabilities, limitations, and advances. Section 3 investigates how smart microgrids can be integrated into urban energy infrastructure and how they increase energy efficiency, resilience, and sustainability. Section 4 will explore frameworks and technologies for sustaining energy planning and microgrid technologies in the next century. Section 5 investigates how smart microgrids can increase cities' resilience and disaster recovery capabilities, especially when designed to be modular and adaptive. Section 6 examines the policy and economic issues that influence the adoption of urban microgrids and recommends solutions to regulatory and financial challenges. Section 7 identifies challenges, future trends, and research directions in the field of smart microgrids in urban settings. Section 8 summarizes key findings, implications, and contributions and offers actionable recommendations for various stakeholders.

2. Current State of the Art of Smart Microgrid Technologies

Smart microgrids integrate distributed energy resources (DERs) such as solar panels, wind turbines, and advanced energy storage systems. These systems rely on energy management systems (EMSs) to monitor and optimize energy distribution, hybrid energy storage systems (HESSs) to improve reliability by combining different storage technologies, and peer-to-peer (P2P) energy trading platforms to facilitate decentralized electricity exchange among consumers. These systems provide flexibility by balancing local energy production, consumption, and storage [12]. With increasing urbanization and the need for sustainable development, smart microgrids play a central role in today's urban energy planning and simultaneously tackle reducing greenhouse gas emissions and grid resilience. The relevance of smart microgrids lies in the fact that they can host multiple sources of energy while delivering stable and reliable power, irrespective of fluctuating demand. They do not apply energy flows from real-time data monitoring, advanced control systems, and sophisticated communication technologies to optimize energy flows [13,14].

Koohi-Kamali et al. [15] explained that smart microgrids can dynamically respond to energy demands, decongesting the central grids and aborting major blackouts. However, high costs, complex integration, and technical limitations of existing DERs are significant barriers to widespread adoption.

However, they present integration challenges in urban settings for renewable DERs, such as solar and wind, since they are intermittent and very volatile. This paper proposes a novel framework for optimizing DERs in urban environments using machine learning. This system correctly predicts energy generation patterns using historical and real-time weather data, allowing for more energy-efficient scheduling and integrating renewable sources. The AI-based framework can reduce energy wastage and manage renewable variability [16]. Optimizing the energy generation time when solar generation is high for cities with their weather pattern and high energy consumption, the framework based on AI proposes to optimize the efficiency and sustainability of urban energy systems by cycling the energy storage cycles. Urban microgrids continuously learn and adapt to the AI framework, which increases resilience and mitigates the impact of sudden weather changes to maintain a reliable power supply [17,18]. Fortunately, Hao et al. [19] demonstrated that AI-augmented predictive models can bring an additional 25% edge compared to traditional methods and have the potential to revolutionize urban energy planning.

The integration of machine learning for optimization of DERs has several advantages. First, it significantly enhances the resilience and greenness of renewable integration by preventing reserves and eliminating fossil fuels. This operational cost reduction not only saves the operational expenses but also syncs with the global sustainability objectives [20,21]. Secondly, since the system is (or maybe) amendable (or adaptable), microgrids can be adaptive to predictable and unpredictable changes in energy supply and demand, thus improving the overall system stability. Furthermore, predictions can be improved over time because the AI model will learn from data, improving with each spin [22,23].

However, this sophisticated system is not easy to employ. The major problem stems from the need for intense data infrastructure for real-time monitoring and data collection. Advanced sensors, communication networks, and data processing capability infrastructure for this deployment may be costly and technologically complex [24,25]. Still, the development of AI and communication networks also brings cybersecurity concerns for the digitalization energy systems, as the capabilities will not necessarily be available to everyone. These are still challenging hurdles to overcome, but the potential of augmenting DER integration with AI-based models holds boundless innovative potential for urban energy systems [23,26].

Using electric vehicle (EV) second-life batteries is a cost-effective solution for storing urban microgrid energy and alleviating environmental and energy efficiency issues. These batteries are badged for automotive applications and thus still possess sufficient energy storage capacity for grid applications and use in low-speed EVs, charging stations, communication base stations, mobile charging devices, and household energy storage systems (ESSs) [27,28]. Second-life EV batteries are cheaper than new batteries, with a second-life battery costing USD 50–150 per kWh of capacity versus a new battery pack with a similar capacity. On the other hand, lithium metal polymer batteries (LMPBs) can reduce carbon dioxide (CO_2) emissions by at least 20% of lead acid and can be used for effective peak shaving and load leveling in an urban environment [29]. According to research, urban microgrids fueled with second-life EV batteries can achieve a 30% reduction in energy costs within five years. Second-life batteries also contribute to a circular economy by minimizing the requirement for new raw materials and decreasing the carbon footprint that battery production creates [30,31]. However, second-life batteries can often have variable performance, and technical challenges in integrating them can restrict their efficiency and lifespan. These challenges are being addressed through advancements in battery management systems and AI-based diagnostics to help second-life batteries become a feasible solution for urban microgrids [32,33].

It describes implementing decentralized control systems in urban microgrids using edge computing and AI. The first is traditional control systems; these are centralized, leading to bottlenecks and increased vulnerability to cyberattacks. With Edge AI technology, local data processing decreases real-time latency and permits smooth responses to energy demand and supply fluctuations [34]. This real-time adaptability is crucial in urban environments with rapidly changing energy needs. By leveraging Edge AI, operational costs can be reduced and system efficiency can be improved through real-time fault detection, corrective actions, and predictive maintenance. The infrastructure is difficult in urban microgrids, and system failures are costly, making this approach particularly appealing [35,36]. Resilience and fault tolerance are improved with decentralized control systems, mitigating risk from potential cyberattacks or network failure. In addition, they increase operational efficiency, providing proactive maintenance with less downtime. It also faces high initial setup costs and complex maintenance and raises data privacy concerns. Advanced renewable energy sources, second-life EV batteries, and distributed control systems revolutionize urban energy management and solve scalability, sustainability, and costs [27,29,37].

However, the traditional grids face limitations. Centralized fossil fuel generation that underlies the traditional energy networks results in high transmission losses and vulnerability to widespread blackouts. On the other hand, smart microgrids combine dispersed renewable energy sources that increase operation reliability due to distributed generation and delivery. In order to achieve these goals, smart microgrids further rely on artificial intelligence (AI) techniques for adaptive control that can carry out self-healing functions and dynamically respond to load storm disturbances in their service is continuous. With increasing demands of urban energy, smart microgrids can adapt to their scale and modularity to lower the scale of infrastructure expansion. Table 1 shows these fundamental differences in smart microgrids compared to traditional grids, demonstrating microgrids' high efficiency, resilience, and environmental benefits. The traditional grids depend entirely on centralized fossil fuel-based energy sources and hence are less sustainable. They have weaknesses such as high transmission losses and slow response to disruptions. In contrast, smart microgrids utilize decentralized clean energy resources, resulting in less loss and more resiliency through islanding capability. Moreover, they are quite different concerning control mechanisms: traditional grids are under centralized control, so they are flexible, whereas AI, running real-time adaptive control mechanisms that increase efficiency and reliability, controls smart microgrids. Finally, smart microgrids are also very scalable and modular, meaning they can be expanded gradually without requiring costly infrastructure upgrades like their traditional grid counterparts. Smart microgrids are also economically sustainable and support the cost-efficient model like the peer-to-peer energy trading model, which helps cope with the dependency on large utilities. However, they still face regulatory challenges. In general, the concept of smart microgrids is to supply a more sustainable, resilient, and available energy solution that matches the energy demands of modern cities.

While PPPs provide financial and infrastructural support for microgrid deployment, they introduce stakeholder alignment and regulatory compliance complexities. To incentivize adoption, governments can introduce policy measures such as tax breaks for private sector investments in microgrids, direct subsidies for pilot projects, and regulatory adjustments that streamline permitting processes for decentralized energy infrastructure. Countries such as Germany and Japan have successfully utilized feed-in tariffs and green energy credits to accelerate microgrid adoption, demonstrating the effectiveness of targeted policy mechanisms. On the other hand, localized energy markets offer greater flexibility but face significant barriers due to inconsistent regulations and technological constraints [7,11]. Adopting standardized regulatory models could bridge these gaps but requires active collaboration between governments, utilities, and private entities. Additionally, the increasing reliance on AI-driven microgrid management systems necessitates discussing cybersecurity threats and data privacy concerns. The effectiveness of AI-based models depends on the availability of real-time data, yet many urban energy infrastructures lack the digital infrastructure to support such advanced optimization techniques [11].

Table 1. Comparison of traditional power grids and smart microgrids.

Feature	Traditional Grid	Smart Microgrid
Energy Source	Centralized, fossil fuel-based	Decentralized, renewable-focused
Reliability	Prone to blackouts and failures	Self-healing, resilient, and adaptive
Energy Efficiency	High transmission losses	Reduced losses through localized generation
Flexibility	Rigid and difficult to expand	Modular and scalable
Control Mechanism	Centralized control	AI-driven, real-time adaptive control
Integration with Renewables	Limited capability	Seamless integration with solar and wind
Response to Disruptions	Slow restoration, centralized dependency	Quick recovery with islanding capabilities
Economic Model	High operational costs, utility-dependent	Cost-efficiency supports P2P energy trading
Regulatory Framework	Highly regulated, slow policy adaptation	Emerging requires supportive policies
Scalability	Difficult and expensive to upgrade	Easily expandable in urban environments

The modern urban power grid benefits from innovative microgrid technologies by increasing energy efficiency and resilience while achieving sustainable power management. The combination of artificial intelligence-based EMSs, HESSs, P2P energy trading, and Edge AI for decentralized control provides significant advantages in optimizing energy distribution and enhancing grid stability. An EMS uses AI algorithms to monitor and optimize energy flows, an HESS combines multiple storage technologies to balance short-term and long-term storage needs, and P2P energy trading allows consumers to buy and sell electricity directly, reducing dependency on centralized grid systems. Smart microgrid technologies experience barriers when deployed due to implementation expenses, system integration difficulties, and regulatory obstacles. The summary table in Table 2 presents the benefits and challenges each smart microgrid technology brings to urban energy infrastructure.

Table 2. Summary of benefits of smart microgrid technology.

Technology	Benefits	Challenges
AI-based EMS	Optimizes energy usage, reduces waste, enhances grid stability	High implementation cost requires extensive data infrastructure
HESS	Improves energy storage efficiency, supports renewable integration	Complex integration, variable performance over time
P2P Energy Trading	Decentralizes energy distribution, reduces reliance on the main grid	Regulatory barriers require blockchain implementation
Edge AI for Decentralized Control	Enhances microgrid resilience, reduces cybersecurity risks	Requires real-time data processing capabilities

3. The Role of Smart Microgrids in Urban Energy Infrastructure

Energy demands are high, infrastructure is complex, and populations are dense in urban environments, which are also vulnerable to disruptions. In traditional urban energy systems, large-scale power plants supply electricity distributed over long distances in centralized grids [38,39]. This centralized model has been working for decades but is highly inflexible, largely lacks resilience, and is limited in sustainability, which will become a far greater issue as cities become denser and the demand for energy increases. Given the rising need to mitigate climate change, cut emissions, and secure the energy supply, smart microgrids are rapidly gaining ground as viable localized energy systems that serve as decentralized alternatives to the prevailing urban energy infrastructure with the possibility of localized generation, storage, and electricity management. These systems are especially well suited to integrating variable resources, optimizing consumption, and enhancing the resilience of the urban grid [40,41]. Smart microgrids can reduce transmission loss, improve energy efficiency, and provide backup power when a power blackout happens, as outlined by Khan et al. [42], and they are an important complementary element in modern urban energy planning. However, their implementation poses unique technical, economic, and regulatory barriers in urban contexts. Figure 1 presents how smart technologies help cities plan for sustainable energy use. The EMS combines devices that capture solar energy through photovoltaic (PV) panels, wind energy, storage systems, and traditional diesel generators. The digital network for distributing energy uses automated systems that help artificial intelligence control edge computing. Through computer system monitoring, AI tools help services run better and work more dependably. The linked system shows how decentralized power systems can best work with smart grids and advanced computing methods to build sustainable urban power structures. Figure 1 shows some features of sustainable planning.

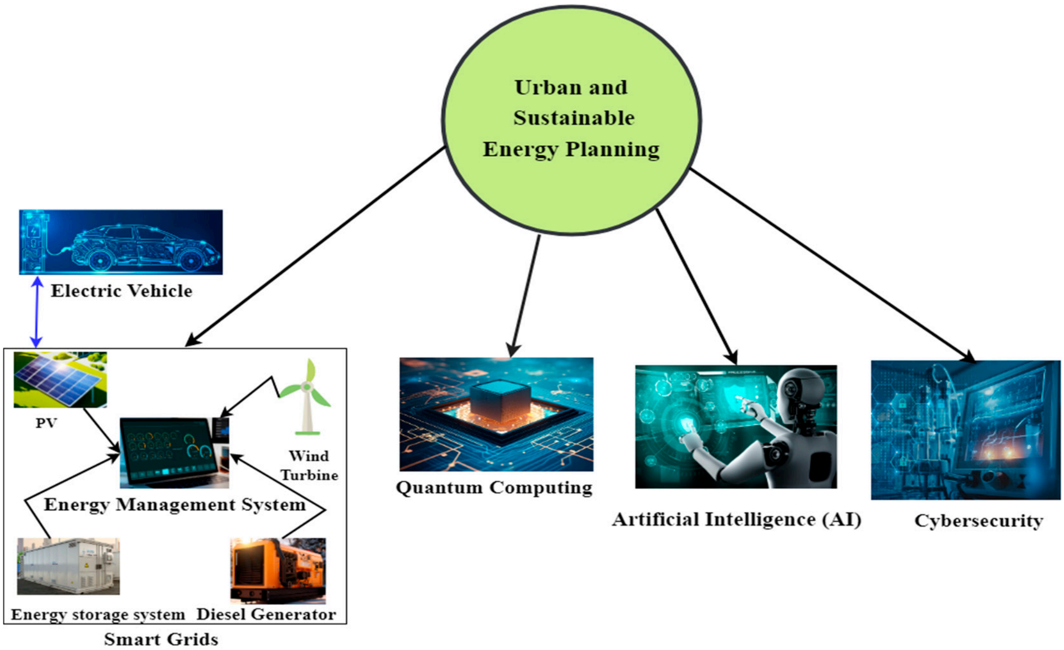

Figure 1. Integration of smart technologies in urban and sustainable energy planning.

3.1. Smart Microgrid Integration in Urban Energy Systems

Integrating smart microgrids into the urban energy infrastructure is a multidimensional process involving technical advancement, policy adjustment, and strategic urban planning. Smart microgrids help cities leverage local renewable sources like solar and wind and are one primary key advantage in powering such cities through DERs [43,44]. Transmission losses and carbon emissions are diminished due to this localized generation, which eliminates dependence on distant power facilities [45]. In recent years, as smart microgrids have been adopted in cities such as San Diego, Barcelona, and Seoul, cities have become the main examples of areas with smart microgrids. It became evident that incorporating smart microgrids into the existing urban energy system demands both a technological innovation policy shift and a strategic approach. The co-generation of electricity and heat, already in use in some cities such as San Diego, Barcelona, and Seoul, is another benefit of microgrids.

For example, in New York City, microgrids are used in areas with high load demands and put off a cut in demand of up to 15% that might have required costly upgrades to the grid. During Hurricane Sandy, which happened in the same year, 2012, microgrids in New Jersey that were integrated with technology persisted in operating when the primary grid went off, a discovery made during disaster circumstances. As we have seen, integrating these examples into the cause also enhances the case of microgrids in cities to provide a secure, green, and sustainable impetus for city development. Achieving such integration at the local level between DERs has proved feasible in these projects, where sophisticated EMSs are used to balance supply and demand. However, adding smart microgrids into current urban grids is problematic due to legacy infrastructure, grid compatibility, and ensuring a reliable and uniform power source [46,47].

Urban energy systems become more flexible and adaptable with smart microgrids. Using localized DERs allows cities to decrease peak load on the main grid, make a more uniform energy distribution, and decrease the risk of blackouts. Implementing microgrids within high energy-consuming neighborhoods in New York City has reduced the 15% peak demand, preventing costly grid upgrades [48,49]. Moreover, smart microgrids can also function as pilot projects to educate cities about carbon-neutral neighborhoods' capabilities to better enable the shift to a more sustainable urban environment. Energy autonomy is another major advantage of using smart microgrids in urban infrastructure. Localized microgrids reduce the vulnerability of cities to shocks from the outside, for example, due to natural disasters and geopolitical events that have disrupted traditional supply chains [50,51]. The chances of microgrids to enhance urban reliability were revealed during Hurricane Sandy in 2012; although the grid itself was almost turned off, some of the microgrids in New Jersey in the affected areas continued to generate electricity [52]. Similarly, Kumar et al. [53] focused on understanding microgrids and presented that decentralizing localized microgrids might decrease vulnerability to the main grid through additional supply mix diversifying, which can improve energy security.

Figure 2 illustrates the integration of smart grids with various urban and industrial energy systems through an EMS. Renewable energy sources such as PV solar panels, wind turbines, and energy storage systems are incorporated into the smart grid, which connects to the electrical grid. The EMS optimizes energy distribution to different urban sectors, including smart cities, industrial zones, and residential areas. This setup enhances energy efficiency, reliability, and sustainability by ensuring a balanced energy supply across diverse infrastructures, reducing dependence on traditional grids, and fostering the transition to renewable energy-driven urban ecosystems.

It makes sense to progress to the inclusion of smart microgrids in the urban environment. First, energy microgrids increase the share of renewables, which will help cities meet their climate objectives. They do not involve energy generated from fossil fuels; they are a localized, environmentally friendly generation within the global emission target [54]. Microgrids have other economic benefits, such as minimizing transaction costs and deferring capital costs for capacity requirements for large-scale grid extension. A flexible layout also improves line utilization, favoring the consumer [55]. However, there are some challenges to integrating smart microgrids into these structures of urban energy systems. Infrastructure development entails capital investment in one instance, which may be burdensome, especially for towns with no budget. Enhancing old grids for new technologies' service requirements is expensive and stressful [41]. Also, it describes the simplicity of how microgrid operating management faces the challenge of integrating with the currently dominant centralized framework, thus leading to an incompatibility issue that requires the use of complicated software and management strategies to carry out the required operation of the microgrid. Some challenges include regulatory and policy issues, as present energy frameworks may not sufficiently safeguard decentralized microgrid operations, which may mean that standards must be altered [23,56].

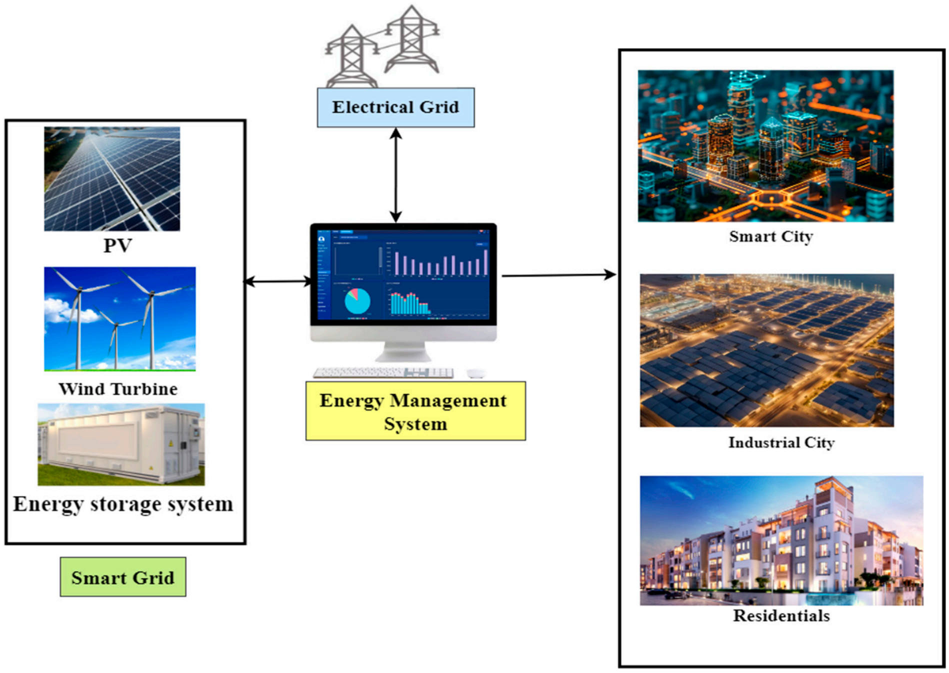

Figure 2. Smart grid integration with urban and industrial energy systems.

3.2. Enhancing Urban Resilience Through Microgrids

The fourth strategic justification for integrating smart microgrids into the urban energy system is to enhance the system's protection against disruptions. Natural catastrophes, acts of cyber-vandalism, and terrorism are disastrous in metropolitan areas and can influence centralized power systems functioning autonomously amid grid outages; brilliant microgrids are strong methods for sustaining fundamental services amid a crisis [57,58]. The resilience of smart microgrids is attributed to their capacity to detach from the primary grid and operate independently during emergencies (a feature referred to as islanding). This capability allows microgrids to continue to serve critical loads such as hospitals, emergency centers, and transportation when the aggregated grid is affected [59,60]. For instance, microgrids were installed in fire-vulnerable areas within California to ensure that the parts of the state termed as essential are not affected by power interruptions during public safety power shutoffs while ensuring the reliability of the entity's operation during emergencies [61]. Moreover, smart microgrids build the ability to develop a remedy even when a failure has not yet occurred using big data analytics. Information flows in from sensors installed in all parts of the urban environment, which can be processed through AI management systems to search for deviations that signal a pressured piece of equipment or one that is about to fail. As for what this has in terms of a proactive element to help avoid outages, it also cuts back on potential expenses related to emergency maintenance [62,63]. Hamdan et al. [64] revealed that the cities incorporating predictive analytical domains in their microgrid systems have improved maintenance costs by 30% compared to other cities and significantly reduced downtimes.

The most important advantage of smart microgrids for achieving urban resilience is the ability to supply electricity around the clock, regardless of the circumstances. Reliability is considered because power failures are credited to extremely severe economic and social impacts in densely populated regions. Also, predictive analytics keeps us busy with preventive actions that reduce the intervals and effects of emergency failures [65,66].

Multiple microgrids may realize load sharing and better resource utilization of resources in a densely populated area, creating a networked microgrid system that enhances grid supply stability. However, there are downsides. The technology and the infrastructure may not be very developed in some parts of the urban world where islanding and predictive analytics would be applied. Installing and supporting software and hardware in those regions or communities with primitive grid systems is very expensive [67,68]. However, it is important to realize that while predictive analytics can help improve maintenance schedules, it depends on adequate data to process, which may not be present due to equipment constraints and/or data errors and/or omissions. A massive investment in technology and training is required to manage such challenges, especially in developing effective communication systems capable of near real-time data exchanges [69].

4. Sustainable Energy Planning and Microgrid Technologies

Sustainable energy planning becomes more crucial as cities become larger and energy demands rise globally. Many cities are turning to decentralized systems such as smart microgrids that integrate renewable energies to reduce greenhouse gas emissions and adapt to climate change pressures [70,71]. Nieuwenhuijsen et al. [72] indicated that over 70% of global carbon emissions come from urban centers, so robust and forward-looking energy strategies are needed. However, even modern smart microgrid technologies have yet to fully address these issues, with long-term sustainability and adaptability still challenging [73]. Much of the existing literature, as reported by Tengilimoglu et al. [74], suggests that existing technologies cannot meet future urban demands under extreme environmental conditions.

Figure 3 highlights the core elements contributing to sustainable energy planning and microgrid technologies. At the center, sustainable energy planning integrates multiple advanced technologies to enhance energy efficiency and resilience. The key components include AI-driven predictive analytics for long-term energy forecasting, the intelligent integration of renewable energy sources to ensure sustainability, hybrid energy storage systems for optimized efficiency, and advanced grid management through AI and blockchain. These interconnected components facilitate decentralized energy distribution, improve grid stability, and support the transition toward more sustainable and intelligent energy systems.

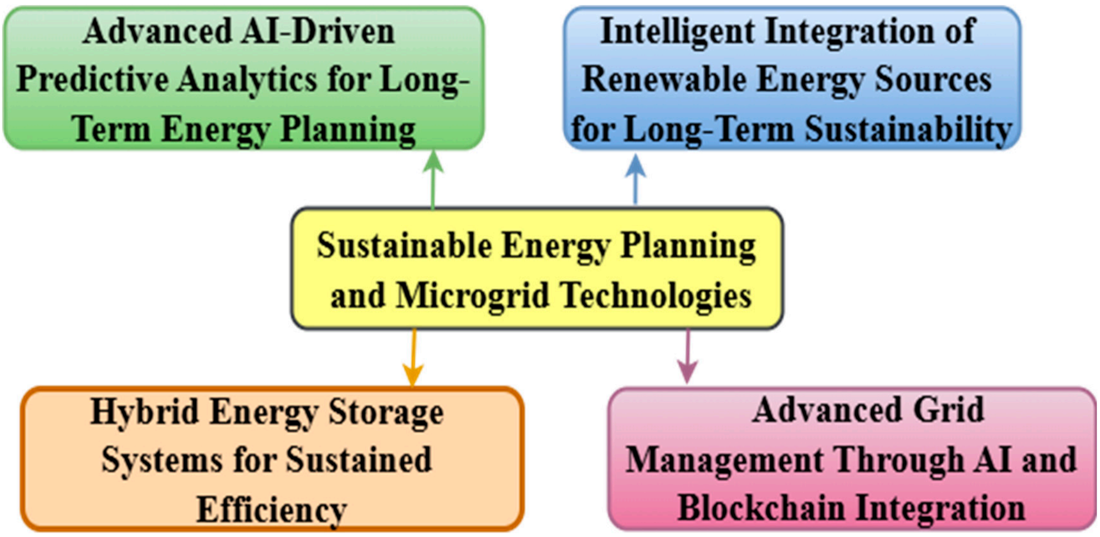

Figure 3. Sustainable energy planning and microgrid technologies.

4.1. Advanced AI-Driven Predictive Analytics for Long-Term Energy Planning

Smart microgrid management relies on predictive analytics to better predict energy needs and efficiently incorporate renewables. While existing predictive models are often short-term, they attempt to predict immediate energy consumption trends and weather conditions [75,76]. This review posits that energy demands projected decades into the future can be predicted by an advanced AI-powered predictive analytics system to secure the sustainability of urban microgrids well into the future. The proposed system would use deep learning algorithms that take advantage of large datasets such as historical energy consumption, urban developments, climate projections, and socioeconomic trends. With this predictive capability over the long term, urban planners could proactively adjust to the energy infrastructure to meet future demands instead of acting on them immediately [77,78]. For instance, in areas likely to face more extreme weather conditions owing to climate change, the system could advise on the reinforcement of solar and wind infrastructure or the smart growth of energy storage systems. It could optimize the deployment of microgrids through AI-driven predictive analytics to identify the most efficient configurations of DERs, the least energy losses, and the highest renewable penetration. In an urban context, this would allow solar PVs and wind turbines to be situated in the highest potential areas through planning optimization while strategically placing battery storage to help balance supply and demand fluctuations [79,80]. According to their study, Haji-Aghajany et al. [81] proved that AI-enhanced forecasting models can curb up to 20% more 'wasted' energy than the average system. Since these models are suitable for 5–10 years, they are rarely helpful in long-term strategic planning.

Predictive algorithms should be strengthened to add real-world energy datasets for the sake of the validity of these models. For instance, using historical energy consumption data from New York City would offer a practical validation framework. In the Amsterdam Smart Grid Project, real-time data were collected, and machine learning was used to optimize by producing better forecasting accuracy and system efficiency [82]. The existing predictive analytics models on energy demand revolve around short-term adaptability, utilizing different machine learning techniques to manage turns and peaks in days, weeks, or even months [83,84]. For example, Ibegbulam et al. [85] also emphasized the role of AI in optimizing the daily energy flows within microgrids. However, these systems cannot predict the long-term effects of demographic changes, technological improvements, and environmental changes. The proposed system bridges the gap with a projection of several decades, and its overall view on future energy landscapes enables informed urban energy planning in the long term. The main innovation is in the depth and breadth of the data inputs and the long time horizon. This system incorporates climate change scenarios, technology advancements, and urbanization patterns into models before 2080 and beyond to extend beyond the constraints of current models. Advanced AI algorithms constantly learn and evolve as they encounter new data, meaning energy planning stays relevant over time as the situation evolves. Being proactive instead of reactive, this innovation makes urban energy planning more resilient and adaptive [86,87].

4.2. Hybrid Energy Storage Systems for Sustained Efficiency

A major hurdle in maintaining the sustainability of urban microgrids is energy storage. While current technologies like lithium-ion batteries are effective, they still have the pitfalls of low energy density, short lifespan, and high environmental impact [88]. This review proposes a hybrid energy storage system involving solid-state batteries, hydrogen fuel cells, and flow batteries to guarantee the longevity and efficiency of microgrids beyond this century. However, solid-state batteries, which employ solid electrolytes instead of liquid ones, are gaining ground as more capable alternatives to conventional batteries because of their higher energy density, safety, and lifetime. Being compact and efficient storage solutions, they are well suited for urban environments where space is limited. They are known to produce clean energy and can provide a complementary storage option compared to batteries, converting stored hydrogen into electricity without creating pollutants [89]. This makes them very appealing to carbon-neutral cities. This scalable, flexible, and integrated storage option is flow batteries, which store energy in liquid electrolytes and can offer large energy capacities required for urban microgrids. By integrating these technologies into one hybrid system, there would be a means of building a dynamic and adaptive energy storage network [90,91]. Flow batteries could manage seasonal energy shifts, hydrogen fuel cells could supply backup power during prolonged periods of low renewable generation, and solid-state batteries could handle daily changes in energy demand. The tiered approach to urban microgrids ensures that these systems are efficient and can take the rising unreliability of energy supply and demand caused by climate change [92,93].

The existing literature tends to address individual storage technologies rather than integrating them into a whole. While Ren et al. [94] showed that solid-state batteries are better for small-scale applications and Nyangon and Darekar [95] focused on the benefits of hydrogen fuel cells for decentralized grids. Nevertheless, this does not consider hybrid strategies that use each type of storages' benefits. The proposed hybrid system completes the gap and can offer a full solution, fulfilling the short- and long-term storage requirements and enhancing microgrid flexibility in an urban environment. Table 3 compares the proposed hybrid energy storage system and conventional lithium-ion batteries, highlighting the trade-offs between cost, efficiency, and scalability. The proposed system, designed with modularity, is adaptable to various energy scenarios. Different storage technologies combine into a hybrid system that is not dependent on a single solution for dealing with market, technological, and environmental failures. Through adaptability, urban microgrids can maintain high efficiency and reliability in this venue over the next century, with the energy density limitations of batteries today, while avoiding the potential environmental concerns of traditional storage options [91].

Table 3. Comparison of hybrid energy storage vs. lithium-ion batteries.

Metric	Lithium-Ion Batteries	Hybrid Energy Storage Model
Energy Density	High	Variable (depends on storage type)
Cycle Life	~5000 charge cycles	Higher due to diverse storage technologies
Efficiency	85–95%	70–90% (varies by storage component)
Cost per kWh	USD 137 (2023 estimates)	Higher initial cost but lower operational costs
Scalability	Limited by material availability	High scalability, modular approach
Environmental Impact	Resource-intensive recycling challenges	Reduced dependence on rare materials

4.3. Advanced Grid Management Through AI and Blockchain Integration

An advanced control system is required to manage the complexity of urban microgrids, handle many data inputs, and achieve secure and efficient operation [3,96]. This review proposes improved AI and blockchain-based EMSs to optimize energy flows, improve security, and promote transparency in urban microgrids. However, involving AI and blockchain in EMSs makes the existing microgrids much more efficient and secure, but at the same time, they incur considerable computational and energy costs. Deep learning models and AI algorithms necessitate intensive computations that, in turn, need high-performance processing units and increase energy consumption in the overall system. Secure energy transaction also demands many computational resources to be integrated into the blockchain platform based on energy-intensive consensus mechanisms like Proof of Work [97]. Further, as the microgrid grows, so do the demands on the data process, which, if the infrastructure is not kept up, can cause bottlenecks. AI helps to make predictions regarding the maintenance of machines or energy optimization, and blockchain guarantees the security of transactions, but a robust digital infrastructure for real-time data collection, storage, and processing should support these technologies. Ensuring scalability requires careful consideration between integrating the technology and enhancing the infrastructure while conducting a cost–benefit analysis in urban microgrid deployment [96,97]. The integrated system would address key issues of smart microgrids' data management, cyber security, and scalability (and consequently viability) of smart microgrids. In order to implement the proposed EMSs, an AI component based on machine learning algorithms would be incorporated into the EMSs, which receive the data from the DERs, storage devices, and consumer behavior in real-time to perform exact load balancing and energy dispatch [97,98]. This translates into a dynamic optimization that reduces waste energy, preserves the energy reserve, and adaptively controls energy flow under real-world conditions, such as sudden increases in demand or decreases in renewable generation. In addition, blockchain technology provides a secure and decentralized place for executing energy transactions in the microgrid and enables a smart, transparent, and secure P2P electricity market with no central intermediaries [99,100]. In an urban environment, however, microgrids would scale using AI and blockchain more easily with new DERs added to the network and as the microgrid is expanded along with the city's growth. For example, AI can forecast peak demand and turn on battery storage appropriately, and blockchain can automatically validate and record energy trade [23,101]. Moreover, Li et al. [102] indicated that AI can enhance security and transparency while increasing 30% energy efficiency. However, these benefits are typically treated apart rather than as a single unit.

Figure 4 illustrates the integration of AI and blockchain within an EMS to enhance smart grid functionality. The smart grid incorporates renewable energy sources such as wind turbines, PV panels, and energy storage systems. The EMS, positioned centrally, facilitates integration by ensuring cybersecurity and efficient data management. AI optimizes energy usage and predictive analytics, while blockchain enhances security and decentralization. The system connects to the electrical grid and efficiently manages loads, including electric vehicles and residential energy consumption, promoting sustainability, reliability, and resilience in modern energy infrastructures.

Existing conventional EMS solutions tend to be centered on (lacking scalability) and are prone to cyberattacks by centralized control systems. Trivedi and Khadem [101] discussed the benefits of combining an AI-driven EMS with small-scale microgrids, and Egunjobi et al. [103] studied the use of blockchain for energy transactions. Unfortunately, integrating AI and blockchain into a single unified EMS that manages complex urban environments still involves a mismatch. This proposed system fills a major gap in the current research to address the need for a distributed, secure, and adaptable management approach that can scale with urban growth [8]. The novelty of the AI- and blockchain-based EMS is that it combines uninterrupted advanced data analytics with secure transaction platforms. Moreover, this innovation improves the urban microgrid's operational efficiency and helps it resist scalability-related issues and cybersecurity threats. This adaptivity is good because their grid can keep up with technological enhancements and remain secure and transparent while the energy load grows into the next century. Thus, these urban microgrids are not merely power suppliers but elastic and resourceful energy ecosystems [97,98,104].

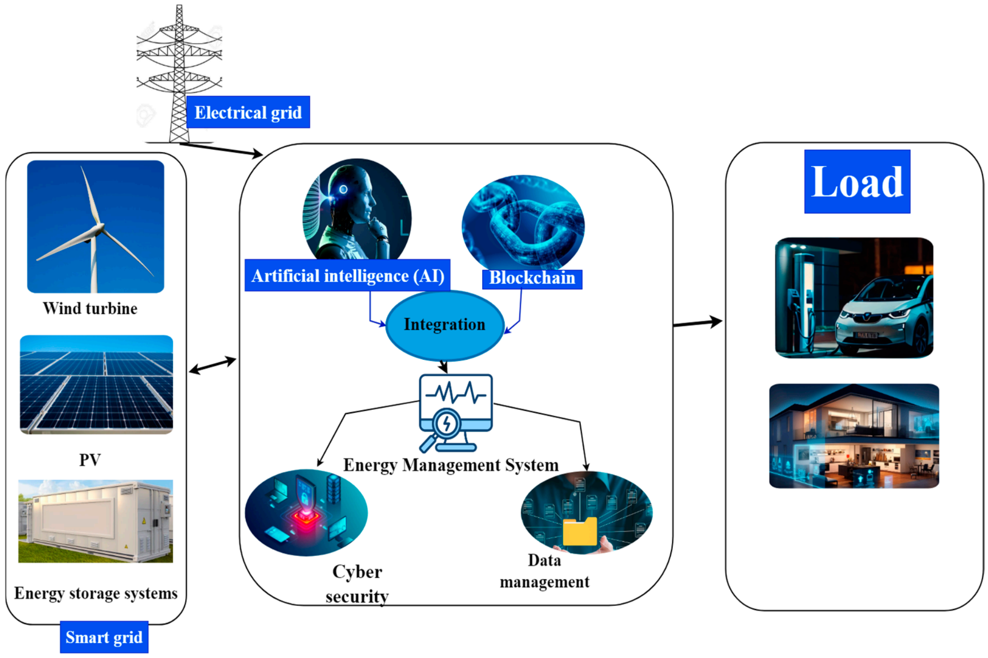

Figure 4. Advanced grid management through AI and blockchain integration energy management system.

4.4. Intelligent Integration of Renewable Energy Sources for Long-Term Sustainability

Instead, the cleanup of carbon emissions in urban areas must be coupled with integrating renewable energy sources (e.g., solar, wind, and biomass) into urban microgrids. However, by its nature, renewable energy has 'unpredictability', making a stable energy supply difficult [105]. This review proposes a new smart integration framework for optimally using renewables in urban environments through adaptive energy forecasting, AI-driven energy storage allocation, and grid flexibility leverage. The framework utilizes AI to forecast renewable energy output based on weather patterns, trends in energy consumer consumption, and grid conditions. It lets the system predict greater or lower renewable output times and then adapt energy storage and dispatch strategies in real-time. The system could be programmed to identify solid-state batteries to first charge when the sun is at its brightest and vice versa; to illustrate, if the sun is hidden, the system can switch to hydrogen fuel cell backup. With this smart allocation, urban microgrids can take up high levels of renewable integration without sacrificing grid stability [106,107].

Additionally, the framework contains several grid flexibility mechanisms that permit the urban microgrid to change gracefully among varying energy resources and storage units subject to their availability and demand. This flexibility reduces individual component wear and tear, increases microgrid assets' lifecycles, and improves efficiency [108,109]. According to Panda et al. [110], the operational and management costs could be reduced to 25% upon the smart integration of renewables. Despite this, most current integration models do not incorporate the predictive and adaptive qualities necessary to manage complex energy landscapes over the long term.

Most studies, including Bamisile et al.'s [35], are related to the short-term optimization of renewable integration coupled with predictive analytics, which focuses on maintaining a balance between supply and demand on a real-time basis. However, these models are static and ill-equipped for the complexities of future urban environments. This gap is to be filled by introducing a time-dynamic, long-term solution that adapts dynamically to changes in conditions (weather, transportation, and renewables). Additional renewables are always desirable for urban microgrids without compromising on future uses. This innovation is grounded holistically and adaptively in integrating renewables and is based on a paradigm different from static energy management models. This framework takes advantage of AI-driven forecasting, intelligent storage allocation, and grid flexibility and is a sustainable solution that can grow with technological advancements and environmental change [111,112]. This keeps urban microgrids at the forefront of renewable energy, suitable for the sustainability targets for the next century and beyond.

5. Smart Microgrids, Resilience, and Disaster Recovery in Urban Settings

Natural and artificial disasters inflict vulnerability on urban environments today. This study identified risks to the stability of urban energy systems associated with multiple factors: climate change, aging infrastructure, urban density, and cybersecurity threats. Since traditional centralized grids are large-scale, interconnected, and thus prone to cascading failures from localized disturbances, they are especially vulnerable [113,114]. Over the past years, the need for smart microgrids in disaster resilience has emerged as an alternative method of intelligent devices to help improve cities' resiliency to any disaster [115]. A smart microgrid contains localized suppliers of power generators, energy storage, and distribution that work independently of the primary grid when needed. The Brooklyn Microgrid is a good example in New York, where peer-to-peer energy trading is allowed through blockchain technology, while the Sendai Microgrid in Japan still functioned and supplied power in the 2011 earthquake and tsunami, an example of resilience.

Furthermore, the German Wildpoldsried Microgrid successfully combines renewable energy to produce surplus electricity, while the Jeju Smart Grid Demonstration Project in South Korea has experimented with large-scale energy automation solutions. These examples show the ability of smart microgrids to work under different urban conditions and reinforce disaster-prone regions. This ability to 'island' during emergencies makes them irreplaceable for critical infrastructure needing uninterruptible power, like hospitals, communication networks, and emergency response support facilities [115,116]. Current smart microgrid systems, however, have their resilience limited by technological, infrastructural, and economic constraints. Table 4 contrasts traditional centralized grids with smart microgrids in disaster scenarios. Traditional grids face large-scale failures, whereas smart microgrids offer localized resilience through islanding and modular adaptability, making them essential for critical infrastructure.

Table 4. Characteristics of smart microgrid resilience in disaster recovery.

Feature	Traditional Grid	Smart Microgrid
Reliability	Vulnerable to cascading failures	Self-healing and localized power resilience
Island Mode Capability	Non-existent	Can operate independently during outages
Recovery Speed	Requires extensive grid repairs	Rapid restoration due to modular structure
Energy Source	Centralized fossil fuel-based power plants	Decentralized renewable sources
Flexibility	Rigid, slow adaptation	Modular and adaptable to changing conditions
Cybersecurity Risks	High vulnerability to cyber threats	AI-driven threat detection and response

5.1. Adaptive Microgrid Architecture for Enhanced Resilience

The effectiveness of smart microgrids during and after a disaster depends on their architecture, proposing an adaptive microgrid architecture that emphasizes modularity, redundancy, and flexibility to make its response and recovery from disruption rapidly. However, Table 5 summarizes how smart microgrid features contribute to resilience and disaster recovery by ensuring adaptive energy control, rapid fault detection, and uninterrupted power supply. Typically, traditional microgrid designs are static, making it difficult to respond optimally to ever-changing conditions or unexpected failures [117,118]. While such an architecture would rely on off-the-shelf building blocks, these would be integrated by some form of adaptive architecture that comprises modular components that could easily be reconfigured or swapped out to enhance the system's ability to operate during emergencies [119]. Quick upgrades, repairs, and scaling, as required for urban environments with varying energy demands, are made possible by the modularity of microgrid design. For example, in a natural disaster, the components of battery units, inverters, and control system modules can be swapped out without changing the whole system [120,121]. This flexibility does more than minimize downtime, it allows for easy integration of new technology as it becomes available. The system provides redundancy, guaranteeing that critical loads can be maintained even when one or more components fail, providing a backup for vital urban activities. Since this adaptive architecture is particularly relevant for urban areas vulnerable to extreme weather events like hurricanes, floods, and wildfires, the infrastructure in these areas can sustain massive damage. The rapid deployment of microgrids designed with modular components allows cities to quickly roll out temporary energy sources, helping restore power to critical sectors, even as larger repairs occur [120,122]. Galvan et al. [123] showed that modular microgrids are ideal for disaster-prone areas, owing to a 40% reduction in restoration times vis-a-vis traditional systems. Nevertheless, implementations of this method are predominantly not truly scalable and flexible but instead built for small/insulated projects [123,124].

Table 5. Smart microgrid features enhancing disaster resilience.

Feature	Description	Benefit
Island Mode Operation	Can disconnect from the main grid during outages	Ensures continuous power supply for critical infrastructure
Modular Architecture	Uses interchangeable energy storage and control units	Enables rapid system restoration and upgrades
AI-Driven Predictive Maintenance	Uses machine learning for early fault detection	Reduces system failures and enhances reliability
Decentralized Control	AI-based real-time energy optimization	Improves response time and grid flexibility
Renewable Energy Integration	Uses solar, wind, and hybrid storage	Reduces reliance on fossil fuels and improves sustainability

Current research has been focused on designing resilient microgrids that can operate autonomously when the grid is out. However, many studies, such as those by Parhizi et al. [125], study isolated microgrids or microgrids designed for certain limited, small-scale applications (e.g., household and campus). Beyond these, the proposed adaptive architecture overcomes these limitations by including a modularization that can be enlarged or diminished to suit the requirements of various urban environments. However, a key gap in the current literature is the lack of attention to large-scale urban deployment under different conditions, which they can offer. The ultimate innovation in the proposed architecture lies in its modularity and flexibility, which contribute to the resiliency of urban microgrids to unforeseen events and the adaptation of urban microgrids to ongoing technological advancements [41,126]. Since urban microgrids can be adapted to continuously update and improve with continued urban and energy technology evolution over the next century, these urban microgrids stay current with cities and the current use of technology because the individual components can be reconfigured without having to reconfigure all of the systems, and disaster recovery efforts are also more cost-effective, lessening the economic impact on urban areas experiencing high levels of disruption [41,127].

5.2. AI-Powered Disaster Prediction and Response Systems for Urban Microgrids

The objective is to predict the disaster accurately and have real-time response capability so that the impact of the disaster on the urban energy system can be minimized. This review suggests the development of AI-based disaster prediction and response systems that use machine learning and real-time analytics to predict and avoid disasters for urban microgrids. These systems would utilize satellite data, weather forecasts, social media feeds, and IoT sensors to forecast potential threats and prepare urban microgrids for them. It would create an AI-powered system that would assist urban microgrids in optimizing their operations before, during, and after any disaster. For instance, in an incoming storm, predictive algorithms might forecast weather patterns and estimate the odds of disruption of electricity in particular communities [127,128]. The system could reactivate backup generators and be ready for use. They could go into off-grid mode and transfer stored energy to critical areas, thus reducing the disruption to essential services. If the system were transitioning through the disaster, real-time data analysis would allow the system to identify faults and create new energy flow routes instantaneously, minimizing the risk of cascading failures [128,129]. AI-powered response systems also help with making post-disaster recovery efforts more efficient. Once damage reports, sensor data, and repair timelines are analyzed, AI can optimize the arrival of maintenance crews and resources to areas with the biggest impact on grid stability [130]. However, a study by Dai et al. [131] confirms that AI systems for disaster management can shrink restoration times by 60% and, at the same time, improve urban resilience. Most existing systems were not designed for multi-layer urban environments in which the scale and diversity of threats are even higher.

Although AI and machine learning have been used in disaster management in energy systems, existing models only consider reactive decisions and not proactive and predictive decisions [132]. In particular, Biswal et al. [133] highlight the significant role of AI in optimizing energy dispatch during events; however, their models are insufficient to support integrated predictions at scales required for large-scale urban deployment. The proposed AI-powered system blends predictive analytics with real-time response, thus providing a holistic approach to disaster resilience specific to the urban context to fill this gap [133,134]. This innovation unifies predictive and real-time analytics into a single system capable of handling the diversity of urban threats. Moving disaster management from a reactive to a proactive stance dramatically reduces the effect of emergencies on an urban population. AI algorithms are adaptable, meaning the system remains effective as new threats and urban landscapes change [135]. This approach's utility lies in increasing the resilience of urban microgrids and contributing to the long-term sustainability of the energy systems, capable of withstanding worsening and greater occurrences of climate-related events through the next century [136].

5.3. Advanced Materials for Durable and Resilient Energy Infrastructure

Urban resilience highly depends on the durability and reliability of energy infrastructure components with the emerging effect of severe, unpredictable, and increasing climate events. The proposed integration of advanced materials in this review to the urban microgrid components includes high-performance composites, phase change materials, and smart alloys to improve the robustness and longevity of the resilient urban microgrid components. These materials can withstand extreme conditions, ranging from intense heat and cold to catastrophic winds and flooding, so urban microgrids remain operational during and after disasters. High-performance composites combine strength and flexibility and are ideal for creating resilient infrastructure components, power lines, transformers, and storage [137,138]. These materials are physically stressed but resist high winds, debris, and impacts during natural disasters.

Furthermore, energy storage systems can employ phase change materials (PCMs) to keep temperatures stable and prevent them from rising above the maximum threshold. Extreme conditions require electrolyte protection from thermal damage, and this is achieved by the PCMs that absorb excess heat and slowly release it, thereby protecting the battery components [139,140]. Shape memory properties in smart alloys enable them to be applied to structural components of microgrids to adjust automatically and recover from deformation with external forces. For instance, smart alloys could create power line supports that bend and bounce back after high winds or impacts, thus reducing the need for immediate repairs [141]. Ajirotutu et al.'s [142] research suggests that advanced materials in urban infrastructure can extend energy systems' lives by 30% and decrease maintenance costs. Such materials, however, have yet to be studied in the current literature about smart microgrids in terms of their long-term performance under varying urban conditions [143].

The most existing research on advanced materials for energy infrastructure targets individual applications, as in the case where batteries or their components are made intrinsically stronger and/or various structures are intrinsically reinforced [92]. While studies such as Ang et al. [144] do not examine their design features of high holistic integration potential, what is not explored is how to integrate advanced material properties across a whole system, such as urban microgrid systems. This gap is addressed by a comprehensive framework for improving the resilience of a microgrid's critical components, including energy storage systems, transmission lines, and others, through diverse material technologies. What is new is the cross-domain application of advanced materials, shifting from single-component improvement to a system-level approach to achieve resilience. The durable use of materials across all elements of the urban microgrid provides for robust and reliable microgrid operation under extreme conditions [58,136]. This approach responds to current climate challenges and is specifically designed for future urban landscapes, focusing on long-term durability and adaptability. Urban planners can invest in strong and flexible materials, producing sustainable and resilient energy systems to the perils of the next century [145].

5.4. Integrated Community Microgrid Networks for Disaster Recovery

Recovery: The outcomes of microgrid networks include reducing 60,000 tons of CO_2 per year through the enhanced use of localized renewable energy and reducing the community's lifecycle carbon emissions by 60% with the plan's implementation [146]. Local microgrid deployments can dramatically increase urban resilience if integrated into a community microgrid network. Interconnected microgrids in a city are connected to allow for coordinated sharing of resources and loads so that all microgrids will receive mutual support to protect themselves during an emergency [41]. This approach increases the redundancy and reliability of the energy system in the urban context and associated reliability in the presence of widespread disruptions. Incorporating urban populations into integrated community microgrid networks facilitates the more efficient management of energy resources, particularly in times of crisis [147,148]. As the network of microgrids compensates by deploying more power from nearby microgrids to lighten the load from the outage of a localized area, residents and critical infrastructure see significantly less effect from the outage. It also makes it possible to optimally use renewable resources to generate and transfer energy from one district (that may have surplus solar energy that did not offset demand from its residents) to a district with lower generation (so that the city avoids wasting solar generation) [58]. Moreover, the energy flow management for disaster recovery is simplified with integrated networks. AI-powered systems can allocate resources across the networks in a coordinated manner, prioritizing and allocating repair efforts according to real-time data. In this case, after the passage of a major storm, the network could automatically cut off damaged sections, reroute power, and send repair crews to the most damaged areas first [149,150]. According to Thirumalai et al. [151], integrated networks decrease downtime by up to 35% versus standalone microgrids, supposedly evidencing the efficacy of a collaborative approach to urban resilience.

Although Wang et al. [152] and other recent studies focus on the resilience of individual microgrids, no prior work examines the possibilities open in potentially interconnected networks. Isolated microgrids effectively sustain localized power during outages, but they sorely miss redundancy and resource sharing of the type offered by integrated networks.

The proposed community network model helps fill this gap by emphasizing how interconnection can increase the overall urban resilience of a city, as well as enable a stronger, more coordinated approach to disaster response. The innovation moves from isolated energy systems to more integrated, connected, coordinated, and collaborative ones to enhance urban resilience. This strategy is a city-wide safety net that eliminates the shortcomings of microgrid deployments, in which limited resources can be shared and redistributed as needed. Integrated networks are energy-secure yet flexible and redundant in the face of increasingly severe environmental challenges [145,153,154]. This forward-looking model responds to the requirement of a scalable and flexible energy solution, adapting to future urban environments' dynamic natures.

6. Policy and Economic Considerations for Smart Microgrids in Urban Areas

The successful implementation of smart microgrids in urban environments depends on a combination of policy, economic, and technological factors. These frameworks enable infrastructure development, regulatory compliance, and investment incentives [155]. While the traditional energy industry relies on centralized grids managed by large utilities, transitioning to decentralized smart microgrids necessitates a fundamental shift in policy and economic models to facilitate large-scale adoption [156]. The opportunity to incorporate renewable energy sources into smart microgrids, improve energy consumption, and increase urban resilience is beneficial. However, barriers such as regulations, financial constraints, or a fragmented policy landscape often hinder large-scale adoption [156,157]. It also presents a holistic regulatory framework for urban microgrid adoption, including flexible standards, streamlined permitting, and financial incentives. Contemporary regulatory environments are often not specific or flexible enough to adjust to the specific characteristics of urban microgrids. Therefore, they have lengthy approval processes and high costs. The regulations can then be scaled to the size and complexity of the urban microgrid via a flexible policy framework, with simpler regulations imposed on smaller neighborhood-scale microgrids and more rigorous standards enforced on larger district-scale urban microgrids [158,159]. Microgrid deployment became faster as bureaucracy hurdles were streamlined. As part of this proposed framework, financial incentives such as tax breaks, grants, and low-interest loans are envisioned [160]. Policymakers can work to encourage private investment in urban microgrids through financial incentives tied to measurable outcomes. They can guarantee the effective use of public funds by ensuring the disposition of public proceeds is tempered and calibrated for the appropriate level of scale. Adapting the regulations to fit the actual needs of urban microgrids can overcome the transition gap, and microgrid projects can be more efficient on a larger scale [3,160].

The study highlights economic drivers behind urban microgrid implementation; therefore, smart development models like PPP localized market systems and community investment schemes are most beneficial for this sector. PPP structures enable private funding sources for building large urban microgrids that fulfill public policy requirements. The effectiveness of targeted policies can be strengthened through initial cost-reduction measures, including tax breaks, subsidies, and low-interest loans. The German subsidy program accelerates the adoption of renewable energy microgrids in urban areas through its approach, which other regions can use as a model. Widespread microgrid deployment requirements will be met through streamlined permitting processes alongside standardized grid codes, which regulators should implement [161,162]. Localized energy markets allow microgrid participants—residents, businesses, and local governments—to trade directly with one another, pushing prices down and incentivizing efficient energy usage. However, these markets have large economic benefits and need regulatory support [163]. Community-driven investment schemes rely on grassroots mechanisms to mobilize residents to directly invest in microgrid projects (e.g., through a crowdfunding platform or cooperative ownership). These models consider the financing question for decentralized electricity systems in urban areas and craft a financial ecosystem focusing on the specific needs of urban microgrids. This multifaceted funding package will build and enhance a resilient and versatile energy system that can grow throughout the next century, offering financing options ranging from neighborhood-scale development to city-scale deployment [164,165].

This review proposes dynamic incentive mechanisms for urban microgrids to promote renewable energy integration and long-term sustainability. Microgrid operators can be incentivized with performance-based incentives to achieve environmental and efficiency targets, e.g., decreasing carbon emissions or increasing the penetration of renewables. Incentives can also be provided in direct subsidies, tax credits, or reduced energy tariffs for a project demonstrating sustainability outcomes, like a reduction in energy consumption or price per unit [166,167]. By linking incentives to performance metrics, policymakers can channel investments to projects with readily quantifiable environmental gains. Microgrid operators can also sell their carbon credits to other companies or entities if their emissions exceed permitted limits via carbon trading schemes, representing another powerful incentive toward renewable integration. Green bonds are a long-term financing vehicle for use in urban microgrid projects, allowing a broad pool of potential investors to return on their investment financially [168]. The gap is usually filled by traditional incentive structures that target short-term goals. However, these mechanisms incorporate long-term financial instruments as well as performance-based metrics. These incentives are flexible and dynamic, paying off on continued performance instead of one-time accomplishments, and are therefore suited to the changing urban energy environment. These mechanisms help preserve the viability and attractiveness of urban microgrids for cities seeking to meet sustainability goals by driving long-term investment in clean energy while linking financial incentives to environmental outcomes [169,170].

Further, this review suggests the necessity of developing a standardized policy framework for urban microgrids to deal with the diverse aspects of these projects across different regions. This framework includes universal technical standards, regulatory guidelines, and best practices for microgrids that enable cross-jurisdictional deployment of microgrid technologies. This would decrease the complexity and cost of complying with different regulatory landscapes. Standardized technical standards are key to achieving consistency in safety, performance, and interoperability requirements, making for less complex microgrid designs and deployments. Project approvals have clear regulatory guidelines that can cut down on the delays for different forms of regulations [171,172]. This fosters an open, constructive dialog through a guide of best practices in project management, stakeholder engagement, and public communication. It will create a unified policy framework aggregating microgrid projects for large-scale financing opportunities, fostering collaboration between cities, and developing a global network of resilient urban microgrids. Flexibility and scalability are emphasized in the framework so that regional adaptations can be made with consistency maintained [3,127]. The balance achieved in this study enables the wide adoption of resilient and sustainable energy systems and empowers cities to grow in step with each other, facilitating the clean energy transition worldwide.

7. Challenges, Future Trends, and Research Directions

Despite their potential, many challenges must be overcome to enable the widespread adoption of smart microgrids in an urban environment in a sustainable and resilient way over the long term. These are technical, economic, social, and policy challenges. The integration of diverse DERs, storage systems, and advanced control technologies into legacy energy grids is one of the primary obstacles. Most urban areas' infrastructures are outdated and not designed for the decentralized and dynamic operations necessary for smart microgrids. For instance, with solar and wind power being variable renewable energy sources, advanced EMSs that can do real-time balancing are a crucial necessity that many existing grids do not have. In addition, the cybersecurity implications for interconnected systems create severe vulnerabilities, especially for densely populated urban areas where cyberattacks would affect large areas.

The challenge of costs is also present in terms of the very high initial cost of implementing smart microgrids, which presents a large barrier, especially for cities lacking budgets and resources competing with other priorities. While solar panels, batteries, and other components have fallen, integrating technologies suitable for these microgrids in large urban energy systems is still very expensive. Moreover, no scalable financing models are available, such as long-term PPPs or novel finance mechanisms for municipalities to engage in smart microgrid projects. The adoption of smart microgrids is resisted by resistance to change, lack of public awareness, and regulatory fragmentation. Existing energy policies are commonly envisioned for centralized grids and do not fully support microgrids' decentralized, bidirectional operations.

Future trends are on the horizon to guide the development of urban smart microgrids addressing these challenges. These are trends that also reflect changes in technology, shifts in policy, and changes in societal priorities. Quantum computing is expected to be integrated into the future of microgrids as it will enable predictive analytics and optimization algorithms to take on more complex datasets and immediately adjust energy flows. Large urban networks of DERs would benefit from quantum-enhanced microgrids by better balancing DERs, anticipating disruption, and optimizing resource allocation. As a result of the rapid growth of blockchain technology and decentralized energy markets, peer-to-peer energy trading is possible within microgrids. This trend enables consumers to trade surplus electricity directly with prosumers (those that both produce and consume electricity) and increases energy efficiency while at the same time reducing dependence on central utilities. With urban microgrids increasing connectivity, peer-to-peer trading may fuel the rise in new economic models and more democratic and community-oriented energy systems.

As climate change helps produce more frequent and more severe weather events, the resilience of urban microgrids will grow in importance. Advanced materials and modular components will be used in future designs to work in extreme conditions, while adaptive architectures may enable recovery from disruptions in a short period. Nature-based solutions, such as green roofs and vegetation in solar canopies, could also improve resilience through lower urban heat islands and greater energy efficiency. Urban microgrids are expected to become hybrid systems that creatively combine different sources and storage technologies. Solid-state batteries, fuel cells, and thermal storage are integrated into these unified systems to solve several energy needs. Such flexible, hybrid microgrids will adapt to supply and demand fluctuations and keep the energy system efficient and sustainable.

These trends must be pursued, but several key research areas must be prioritized to grasp their potential. This will fill the existing knowledge gaps and help develop next-generation microgrid technology. Cybersecurity has become an important research area as urban microgrids become increasingly digitalized. Further research should aim to build steadfast, AI-driven security regimes capable of detecting and counteracting hostile campaigns in real-time. Security protocols would be explored based on blockchains, ensuring the integrity of energy transactions and protecting sensitive data. Scaling up from small neighborhoods to urban districts requires research to understand how to maintain these advantages. This encompasses the analysis of modular designs, interoperability standards, and flexible control systems that can respond on small to large scales or from low complexity to high.

Urban microgrids are gaining popularity, and research into their part in carbon neutrality and energy equity should continue. This encompasses analyzing how microgrids can decrease emissions in low-income areas and increase access to affordable and reliable energy. Integrating renewable energy solutions in underserved communities can provide pilot projects that could help replicate the solution worldwide. Wireless energy transfer, nanotechnology-based materials, and bidirectional EV charging systems can be integrated into promising future research avenues. However, the scalability and feasibility of these innovations need to be further verified, as they can improve the efficiency, reliability, and flexibility of urban microgrids. Developing predictive models incorporating demographic changes, technological advancements, and climate scenarios is essential to long-term energy planning decisions. To do this, these models should include technical, economic, social, and environmental dimensions, making them applicable to the holistic approach to sustainable urban development.

There will be a need for collaboration among governments, academia, industry, and communities to help smart microgrid technologies advance. Efficient innovation leverages multidisciplinary research initiatives, PPPs, and international knowledge-sharing platforms to accelerate innovation and better address the challenges. Universities and research institutions will be part of the spectrum of leading new microgrid technologies, while private companies will be tasked with implementing large-scale solutions to these technologies. Collaborative pilot projects are viable tools to demonstrate the feasibility and provide a roadmap for deploying innovative design. Governments need to enable collaboration via the creation of regulatory sandboxes where new technologies and business models can be experimented within a sandbox, with a certain amount of control. This would let the stakeholders try out these innovative approaches independent of the existing regulations and make progress faster. Local communities are involved in planning and developing urban microgrids, so projects are compatible with their preferences. Public support can be built to ensure long-term success through participatory approaches that involve residents in decision-making.

8. Conclusions

Through this review, smart microgrids in urban energy planning are thoroughly analyzed. The key contributions of this research are (1) analyzing the potential of AI-driven EMS for energy optimization, (2) developing an innovative hybrid energy storage model integrating solid-state battery, hydrogen fuel cell, as well as flow battery, and (3) providing an economic and policy assessment on the economic viability with a PPP model and the value of localized energy markets. Lastly, current is a highly valuable and accessible information platform to provide insights into smart microgrids' technology, trends, regulations, and market readiness. Future research should focus on research into regulatory standardization, AI-assisted security framework, and approaches to making smart microgrids scalable for broader adoption. Moreover, it underscores the importance of integrating cybersecurity measures to protect interconnected microgrid networks. Future research should focus on enhancing AI-driven optimization, developing peer-to-peer energy markets, and leveraging blockchain technology for secure transactions. These findings provide a roadmap for policymakers, researchers, and industry leaders to accelerate the transition toward resilient and sustainable urban energy systems. This paper discussed the state of smart microgrid technologies, the challenges and opportunities of their integration into urban energy systems, and the possible innovations that would shape their development for the next century. This paper argued that AI-driven predictive analytics and quantum computing could be utilized in long-term energy planning, hybrid storage systems, and integrating advanced materials and adaptive architectures into microgrid elements. It also addresses economic and policy frameworks for motivating urban microgrid adoption, such as payment for environmental services, centralized permitting, PPPs, localized energy markets, and performance-based incentives. The research agenda primarily focuses on cybersecurity, scalability, and emerging technologies. This review focuses on technical and non-technical dimensions and emphasizes the importance of adopting a holistic approach to promoting smart microgrid technologies in urban contexts.

This review provides many insights with important implications for urban energy planning and policy development. Cities moving to a decentralized, renewable-based energy system can leverage smart microgrids to reduce dependence on traditional centralized grids and increase energy resilience. However, regulatory fragmentation, high costs, and technological limitations remain barriers to overcome, which policymakers, researchers, and industry leaders need to work together on. Flexible regulatory frameworks and outcome-based incentives will be essential to scale up microgrid projects. Policies in one jurisdiction do not need to be applied in other jurisdictions but deploying them can be much easier and quicker if there is a desire to standardize policies across jurisdictions. Continued exploration of advanced technologies, including AI, blockchain, and nanotechnology, is required, specifically in scalability, efficiency, and sustainability. Financing and implementing smart microgrids will be based on PPPs and innovative business models like peer-to-peer energy trading and community-driven investments.

The development of smart microgrids relies on innovation and interdisciplinary collaboration. Research areas of interest include advancing cybersecurity, integrating emerging technologies such as wireless energy transfer and nanotechnology-based materials, developing long-term sustainability models, and developing energy equity models for underserved urban communities. Areas that protect interconnected microgrids from cyber threats allow the integration of emerging technologies and provide predictive tools for future sustainability. Thus, by addressing these research areas, stakeholders guarantee that smart microgrids are constantly developing, providing cities with reliable and sustainable energy for the future.

Smart microgrids shift from the normal approach of central energy planning in urban areas towards a localized, reliable, and more sustainable solution. Technological innovation, if supported by corresponding policies and economic structures, can help cities design the systems currently used to generate power and put in place systems that will serve subsequent generations. Due to the rising level of urbanization and enhanced climate changes, smart microgrids will play a critical role in establishing sustainable and more resilient energy systems. Hence, this review has helped to address some of the existing literature gaps and gaps between current microgrid technologies and their possible usability for long-term urban energy planning. This concerns assessing economic and policy implications for clients and suggesting new frameworks and technologies to solve complex urban problems. These contributions offer a roadmap for the challenges and prospects of smart microgrids as the foundation for future smart urban energy systems.

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References

1. Kohlhase, J.E. The New Urban World 2050: Perspectives, Prospects and Problems. *Reg. Sci. Policy Pract.* **2013**, *5*, 153–166. [CrossRef]
2. Akash, F.A.; Shovon, S.M.; Rahman, W.; Rahman, M.A.; Chakraborty, P.; Monir, M.U. Greening the Grid: A Comprehensive Review of Renewable Energy in Bangladesh. *Heliyon* **2024**, *10*, e27477. [CrossRef] [PubMed]
3. Shahzad, S.; Abbasi, M.A.; Ali, H.; Iqbal, M.; Munir, R.; Kilic, H. Possibilities, Challenges, and Future Opportunities of Microgrids: A Review. *Sustainability* **2023**, *15*, 6366. [CrossRef]
4. Zhang, J. Energy Management System: The Engine for Sustainable Development and Resource Optimization. *Highlights Sci. Eng. Technol.* **2023**, *76*, 618–624. [CrossRef]
5. Amine, H.M.; Aissa, B.; Rezk, H.; Messaoud, H.; Othmane, A.; Saad, M.; Abdelkareem, M.A. Enhancing Hybrid Energy Storage Systems with Advanced Low-Pass Filtration and Frequency Decoupling for Optimal Power Allocation and Reliability of Cluster of DC-Microgrids. *Energy* **2023**, *282*, 128310. [CrossRef]
6. Almihat, M.G.M.; Munda, J.L. Review on Recent Control System Strategies in Microgrid. *Edelweiss Appl. Sci. Technol.* **2024**, *8*, 5089–5111. [CrossRef]
7. Arévalo, P.; Ochoa-Correa, D.; Villa-Ávila, E. A Systematic Review on the Integration of Artificial Intelligence into Energy Management Systems for Electric Vehicles: Recent Advances and Future Perspectives. *World Electr. Veh. J.* **2024**, *15*, 364. [CrossRef]
8. Al Shareef, A.M.; Seçkiner, S.; Eid, B.; Abumeteir, H. Integration of Blockchain with Artificial Intelligence Technologies in the Energy Sector: A Systematic Review. *Front. Energy Res.* **2024**, *12*, 1377950. [CrossRef]
9. Aguilar, J.; Garces-Jimenez, A.; R-Moreno, M.D.; García, R. A Systematic Literature Review on the Use of Artificial Intelligence in Energy Self-Management in Smart Buildings. *Renew. Sustain. Energy Rev.* **2021**, *151*, 111530. [CrossRef]
10. Manuel, H.N.N.; Kehinde, H.M.; Agupugo, C.P.; Manuel, A.C.N. The Impact of AI on Boosting Renewable Energy Utilization and Visual Power Plant Efficiency in Contemporary Construction. *World J. Adv. Res. Rev.* **2024**, *23*, 1333–1348. [CrossRef]
11. Liang, X.; Chen, K.; Chen, S.; Zhu, X.; Jin, X.; Du, Z. IoT-Based Intelligent Energy Management System for Optimal Planning of HVAC Devices in Net-Zero Emissions PV-Battery Building Considering Demand Compliance. *Energy Convers. Manag.* **2023**, *292*, 117369. [CrossRef]
12. Dawn, S.; Ramakrishna, A.; Ramesh, M.; Das, S.S.; Rao, K.D.; Islam, M.M.; Selim Ustun, T. Integration of Renewable Energy in Microgrids and Smart Grids in Deregulated Power Systems: A Comparative Exploration. *Adv. Energy Sustain. Res.* **2024**, *5*, 2400088. [CrossRef]
13. Esfandi, S.; Tayebi, S.; Byrne, J.; Taminiau, J.; Giyahchi, G.; Alavi, S.A. Smart Cities and Urban Energy Planning: An Advanced Review of Promises and Challenges. *Smart Cities* **2024**, *7*, 414–444. [CrossRef]
14. Bompard, E.F.; Conti, S.; Masera, M.J.; Soma, G.G. A New Electricity Infrastructure for Fostering Urban Sustainability: Challenges and Emerging Trends. *Energies* **2024**, *17*, 5573. [CrossRef]
15. Koohi-Kamali, S.; Rahim, N.A. Coordinated Control of Smart Microgrid during and after Islanding Operation to Prevent under Frequency Load Shedding Using Energy Storage System. *Energy Convers. Manag.* **2016**, *127*, 623–646. [CrossRef]
16. Hotaling, C.; Bird, S.; Heintzelman, M.D. Willingness to Pay for Microgrids to Enhance Community Resilience. *Energy Policy* **2021**, *154*, 112248. [CrossRef]
17. Ukoba, K.; Olatunji, K.O.; Adeoye, E.; Jen, T.-C.; Madyira, D.M. Optimizing Renewable Energy Systems through Artificial Intelligence: Review and Future Prospects. *Energy Environ.* **2024**, *35*, 3833–3879. [CrossRef]
18. Liu, Z.; Sun, Y.; Xing, C.; Liu, J.; He, Y.; Zhou, Y.; Zhang, G. Artificial Intelligence Powered Large-Scale Renewable Integrations in Multi-Energy Systems for Carbon Neutrality Transition: Challenges and Future Perspectives. *Energy AI* **2022**, *10*, 100195. [CrossRef]
19. Hao, H.; Wang, Y.; Chen, J. Empowering Scenario Planning with Artificial Intelligence: A Perspective on Building Smart and Resilient Cities. *Engineering* **2024**, *43*, 272–283. [CrossRef]
20. Oladapo, B.I.; Olawumi, M.A.; Omigbodun, F.T. Machine Learning for Optimising Renewable Energy and Grid Efficiency. *Atmosphere* **2024**, *15*, 1250. [CrossRef]
21. Ukoba, K.; Onisuru, O.R.; Jen, T.-C. Harnessing Machine Learning for Sustainable Futures: Advancements in Renewable Energy and Climate Change Mitigation. *Bull. Natl. Res. Cent.* **2024**, *48*, 99. [CrossRef]
22. Ahmad, T.; Zhu, H.; Zhang, D.; Tariq, R.; Bassam, A.; Ullah, F.; AlGhamdi, A.S.; Alshamrani, S.S. Energetics Systems and Artificial Intelligence: Applications of Industry 4.0. *Energy Rep.* **2022**, *8*, 334–361. [CrossRef]

23. Akter, A.; Zafir, E.I.; Dana, N.H.; Joysoyal, R.; Sarker, S.K.; Li, L.; Muyeen, S.M.; Das, S.K.; Kamwa, I. A Review on Microgrid Optimization with Meta-Heuristic Techniques: Scopes, Trends and Recommendation. *Energy Strategy Rev.* **2024**, *51*, 101298. [CrossRef]
24. Li, C.; Chen, Y.; Shang, Y. A Review of Industrial Big Data for Decision Making in Intelligent Manufacturing. *Eng. Sci. Technol. Int. J.* **2022**, *29*, 101021. [CrossRef]
25. Ullah, I.; Adhikari, D.; Su, X.; Palmieri, F.; Wu, C.; Choi, C. Integration of Data Science with the Intelligent IoT (IIoT): Current Challenges and Future Perspectives. *Digit. Commun. Netw.* **2024**, in press. [CrossRef]
26. Kaur, R.; Gabrijelčič, D.; Klobučar, T. Artificial Intelligence for Cybersecurity: Literature Review and Future Research Directions. *Inf. Fusion* **2023**, *97*, 101804. [CrossRef]
27. Sarker, M.T.; Haram, M.H.S.M.; Shern, S.J.; Ramasamy, G.; Al Farid, F. Second-Life Electric Vehicle Batteries for Home Photovoltaic Systems: Transforming Energy Storage and Sustainability. *Energies* **2024**, *17*, 2345. [CrossRef]
28. Azizighalehsari, S.; Venugopal, P.; Pratap Singh, D.; Batista Soeiro, T.; Rietveld, G. Empowering Electric Vehicles Batteries: A Comprehensive Look at the Application and Challenges of Second-Life Batteries. *Batteries* **2024**, *10*, 161. [CrossRef]
29. Dong, Q.; Liang, S.; Li, J.; Kim, H.C.; Shen, W.; Wallington, T.J. Cost, Energy, and Carbon Footprint Benefits of Second-Life Electric Vehicle Battery Use. *iScience* **2023**, *26*, 107195. [CrossRef]
30. Thakur, J.; Martins Leite de Almeida, C.; Baskar, A.G. Electric Vehicle Batteries for a Circular Economy: Second Life Batteries as Residential Stationary Storage. *J. Clean. Prod.* **2022**, *375*, 134066. [CrossRef]
31. Kebir, N.; Leonard, A.; Downey, M.; Jones, B.; Rabie, K.; Bhagavathy, S.M.; Hirmer, S.A. Second-Life Battery Systems for Affordable Energy Access in Kenyan Primary Schools. *Sci. Rep.* **2023**, *13*, 1374. [CrossRef] [PubMed]
32. Börner, M.F.; Frieges, M.H.; Späth, B.; Spütz, K.; Heimes, H.H.; Sauer, D.U.; Li, W. Challenges of Second-Life Concepts for Retired Electric Vehicle Batteries. *Cell Rep. Phys. Sci.* **2022**, *3*, 101095. [CrossRef]
33. Gu, X.; Bai, H.; Cui, X.; Zhu, J.; Zhuang, W.; Li, Z.; Hu, X.; Song, Z. Challenges and Opportunities for Second-Life Batteries: Key Technologies and Economy. *Renew. Sustain. Energy Rev.* **2024**, *192*, 114191. [CrossRef]
34. El-Afifi, M.I.; Sedhom, B.E.; Padmanaban, S.; Eladl, A.A. A Review of IoT-Enabled Smart Energy Hub Systems: Rising, Applications, Challenges, and Future Prospects. *Renew. Energy Focus* **2024**, *51*, 100634. [CrossRef]
35. Bamisile, O.; Cai, D.; Adun, H.; Dagbasi, M.; Ukwuoma, C.C.; Huang, Q.; Johnson, N.; Bamisile, O. Towards Renewables Development: Review of Optimization Techniques for Energy Storage and Hybrid Renewable Energy Systems. *Heliyon* **2024**, *10*, e37482. [CrossRef]
36. Alijoyo, F.A. AI-Powered Deep Learning for Sustainable Industry 4.0 and Internet of Things: Enhancing Energy Management in Smart Buildings. *Alex. Eng. J.* **2024**, *104*, 409–422. [CrossRef]
37. Alrumaih, T.N.I.; Alenazi, M.J.F.; AlSowaygh, N.A.; Humayed, A.A.; Alablani, I.A. Cyber Resilience in Industrial Networks: A State of the Art, Challenges, and Future Directions. *J. King Saud. Univ.—Comput. Inf. Sci.* **2023**, *35*, 101781. [CrossRef]
38. Nik, V.M.; Perera, A.T.D.; Chen, D. Towards Climate Resilient Urban Energy Systems: A Review. *Natl. Sci. Rev.* **2020**, *8*, nwaa134. [CrossRef]
39. Sharifi, A.; Yamagata, Y. Principles and Criteria for Assessing Urban Energy Resilience: A Literature Review. *Renew. Sustain. Energy Rev.* **2016**, *60*, 1654–1677. [CrossRef]
40. Kabeyi, M.J.B.; Olanrewaju, O.A. Smart Grid Technologies and Application in the Sustainable Energy Transition: A Review. *Int. J. Sustain. Energy* **2023**, *42*, 685–758. [CrossRef]
41. Uddin, M.; Mo, H.; Dong, D.; Elsawah, S.; Zhu, J.; Guerrero, J.M. Microgrids: A Review, Outstanding Issues and Future Trends. *Energy Strategy Rev.* **2023**, *49*, 101127. [CrossRef]
42. Khan, K.A.; Quamar, M.M.; Al-Qahtani, F.H.; Asif, M.; Alqahtani, M.; Khalid, M. Smart Grid Infrastructure and Renewable Energy Deployment: A Conceptual Review of Saudi Arabia. *Energy Strategy Rev.* **2023**, *50*, 101247. [CrossRef]
43. Khaleel, M.; Yusupov, Z.; Alfalh, B.; Guneser, M.T.; Nassar, Y.; El-Khozondar, H. Impact of Smart Grid Technologies on Sustainable Urban Development. *Int. J. Electr. Eng. Sustain.* **2024**, *2*, 62–82. [CrossRef]
44. Gerlach, J.; Eckhoff, S.; Breitner, M.H. Decision Support for Strategic Microgrid Design Integrating Governance, Business, Intelligence, Communication, and Physical Perspectives. *Sustain. Cities Soc.* **2024**, *113*, 105672. [CrossRef]
45. Olujobi, O.J.; Okorie, U.E.; Olarinde, E.S.; Aina-Pelemo, A.D. Legal Responses to Energy Security and Sustainability in Nigeria's Power Sector amidst Fossil Fuel Disruptions and Low Carbon Energy Transition. *Heliyon* **2023**, *9*, e17912. [CrossRef]
46. Yang, J.; Kwon, Y.; Kim, D. Regional Smart City Development Focus: The South Korean National Strategic Smart City Program. *IEEE Access* **2021**, *9*, 7193–7210. [CrossRef]
47. Reddy, G.P.; Kumar, Y.V.P.; Chakravarthi, M.K. Communication Technologies for Interoperable Smart Microgrids in Urban Energy Community: A Broad Review of the State of the Art, Challenges, and Research Perspectives. *Sensors* **2022**, *22*, 5881. [CrossRef]
48. Rangarajan, S.S.; Raman, R.; Singh, A.; Shiva, C.K.; Kumar, R.; Sadhu, P.K.; Collins, E.R.; Senjyu, T. DC Microgrids: A Propitious Smart Grid Paradigm for Smart Cities. *Smart Cities* **2023**, *6*, 1690–1718. [CrossRef]

49. Panda, S.; Mohanty, S.; Rout, P.K.; Sahu, B.K.; Parida, S.M.; Samanta, I.S.; Bajaj, M.; Piecha, M.; Blazek, V.; Prokop, L. A Comprehensive Review on Demand Side Management and Market Design for Renewable Energy Support and Integration. *Energy Rep.* **2023**, *10*, 2228–2250. [CrossRef]
50. Mishra, P.; Singh, G. Energy Management Systems in Sustainable Smart Cities Based on the Internet of Energy: A Technical Review. *Energies* **2023**, *16*, 6903. [CrossRef]
51. Calvillo, C.F.; Sánchez-Miralles, A.; Villar, J. Energy Management and Planning in Smart Cities. *Renew. Sustain. Energy Rev.* **2016**, *55*, 273–287. [CrossRef]
52. Gundlach, J. Microgrids and Resilience to Climate-Driven Impacts on Public Health. *Sabin Cent. Clim. Change Law Columbia Law Sch.* **2018**, *18*, 77–130.
53. Kumar, A.; Singh, A.R.; Raghav, L.P.; Deng, Y.; He, X.; Bansal, R.C.; Kumar, P.; Naidoo, R.M. State-of-the-Art Review on Energy Sharing and Trading of Resilient Multi Microgrids. *iScience* **2024**, *27*, 109549. [CrossRef] [PubMed]
54. Nadeem, T.B.; Siddiqui, M.; Khalid, M.; Asif, M. Distributed Energy Systems: A Review of Classification, Technologies, Applications, and Policies. *Energy Strategy Rev.* **2023**, *48*, 101096. [CrossRef]
55. Morris, G.Y.; Abbey, C.; Wong, S.; Joós, G. Evaluation of the Costs and Benefits of Microgrids with Consideration of Services beyond Energy Supply. In Proceedings of the 2012 IEEE Power and Energy Society General Meeting, San Diego, CA, USA, 22–26 July 2012; pp. 1–9.
56. Altaf, M.W.; Arif, M.T.; Islam, S.N.; Haque, M.E. Microgrid Protection Challenges and Mitigation Approaches–A Comprehensive Review. *IEEE Access* **2022**, *10*, 38895–38922. [CrossRef]
57. Hussain, A.; Bui, V.-H.; Kim, H.-M. Microgrids as a Resilience Resource and Strategies Used by Microgrids for Enhancing Resilience. *Appl. Energy* **2019**, *240*, 56–72. [CrossRef]
58. Mishra, S.; Anderson, K.; Miller, B.; Boyer, K.; Warren, A. Microgrid Resilience: A Holistic Approach for Assessing Threats, Identifying Vulnerabilities, and Designing Corresponding Mitigation Strategies. *Appl. Energy* **2020**, *264*, 114726. [CrossRef]
59. Padmavathy, R.; Singh, S.K.; Sindhu, M.; Jasim, L.H.; Saxena, A.; Dari, S.S. Enhancing Power Grid Resilience against Cyber Threats in the Smart Grid Era. *E3S Web Conf.* **2024**, *540*, 10021. [CrossRef]
60. Liu, H.; Huang, L.; Dou, Z.; Wang, S. Campus Microgrid Protection: A Unified Approach against Cyberattacks. *Front. Energy Res.* **2024**, *12*, 1362412. [CrossRef]
61. Moreno, R.; Trakas, D.N.; Jamieson, M.; Panteli, M.; Mancarella, P.; Strbac, G.; Marnay, C.; Hatziargyriou, N. Microgrids Against Wildfires: Distributed Energy Resources Enhance System Resilience. *IEEE Power Energy Mag.* **2022**, *20*, 78–89. [CrossRef]
62. Mazhar, T.; Irfan, H.M.; Haq, I.; Ullah, I.; Ashraf, M.; Shloul, T.A.; Ghadi, Y.Y.; Imran; Elkamchouchi, D.H. Analysis of Challenges and Solutions of IoT in Smart Grids Using AI and Machine Learning Techniques: A Review. *Electronics* **2023**, *12*, 242. [CrossRef]
63. Reka, S.S.; Dragicevic, T.; Venugopal, P.; Ravi, V.; Rajagopal, M.K. Big Data Analytics and Artificial Intelligence Aspects for Privacy and Security Concerns for Demand Response Modelling in Smart Grid: A Futuristic Approach. *Heliyon* **2024**, *10*, e35683. [CrossRef] [PubMed]
64. Hamdan, A.; Ibekwe, K.I.; Ilojianya, V.I.; Sonko, S.; Etukudoh, E.A.; Hamdan, A.; Ibekwe, K.I.; Ilojianya, V.I.; Sonko, S.; Etukudoh, E.A. AI in Renewable Energy: A Review of Predictive Maintenance and Energy Optimization. *Int. J. Sci. Res. Arch.* **2024**, *11*, 718–729. [CrossRef]
65. Loni, A.; Asadi, S. Power System Resilience: The Role of Electric Vehicles and Social Disparities in Mitigating the US Power Outages. *Smart Grids Energy* **2024**, *9*, 23. [CrossRef]
66. Dada, J.O. Towards Understanding the Benefits and Challenges of Smart/Micro-Grid for Electricity Supply System in Nigeria. *Renew. Sustain. Energy Rev.* **2014**, *38*, 1003–1014. [CrossRef]
67. Bordbari, M.J.; Nasiri, F. Networked Microgrids: A Review on Configuration, Operation, and Control Strategies. *Energies* **2024**, *17*, 715. [CrossRef]
68. Hossain, M.A.; Pota, H.R.; Hossain, M.J.; Blaabjerg, F. Evolution of Microgrids with Converter-Interfaced Generations: Challenges and Opportunities. *Int. J. Electr. Power Energy Syst.* **2019**, *109*, 160–186. [CrossRef]
69. Ohalete, N.C.; Aderibigbe, A.O.; Ani, E.C.; Ohenhen, P.E.; Akinoso, A. Advancements in Predictive Maintenance in the Oil and Gas Industry: A Review of AI and Data Science Applications. *World J. Adv. Res. Rev.* **2023**, *20*, 167–181. [CrossRef]
70. Khalid, M. Smart Grids and Renewable Energy Systems: Perspectives and Grid Integration Challenges. *Energy Strategy Rev.* **2024**, *51*, 101299. [CrossRef]
71. Otay, İ.; Çevik Onar, S.; Öztayşi, B.; Kahraman, C. Evaluation of Sustainable Energy Systems in Smart Cities Using a Multi-Expert Pythagorean Fuzzy BWM & TOPSIS Methodology. *Expert Syst. Appl.* **2024**, *250*, 123874. [CrossRef]
72. Nieuwenhuijsen, M.J. Urban and Transport Planning Pathways to Carbon Neutral, Liveable and Healthy Cities; A Review of the Current Evidence. *Environ. Int.* **2020**, *140*, 105661. [CrossRef] [PubMed]
73. Huovila, A.; Siikavirta, H.; Antuña Rozado, C.; Rökman, J.; Tuominen, P.; Paiho, S.; Hedman, Å.; Ylén, P. Carbon-Neutral Cities: Critical Review of Theory and Practice. *J. Clean. Prod.* **2022**, *341*, 130912. [CrossRef]

74. Tengilimoglu, O.; Carsten, O.; Wadud, Z. Implications of Automated Vehicles for Physical Road Environment: A Comprehensive Review. *Transp. Res. Part E Logist. Transp. Rev.* **2023**, *169*, 102989. [CrossRef]
75. El Maghraoui, A.; El Hadraoui, H.; Ledmaoui, Y.; El Bazi, N.; Guennouni, N.; Chebak, A. Revolutionizing Smart Grid-Ready Management Systems: A Holistic Framework for Optimal Grid Reliability. *Sustain. Energy Grids Netw.* **2024**, *39*, 101452. [CrossRef]
76. Khosravi, N.; Oubelaid, A.; Belkhier, Y. Energy Management in Networked Microgrids: A Comparative Study of Hierarchical Deep Learning and Predictive Analytics Techniques. *Energy Convers. Manag. X* **2025**, *25*, 100828. [CrossRef]
77. Wu, P.; Zhang, Z.; Peng, X.; Wang, R. Deep Learning Solutions for Smart City Challenges in Urban Development. *Sci. Rep.* **2024**, *14*, 5176. [CrossRef]
78. Olawade, D.B.; Wada, O.Z.; David-Olawade, A.C.; Fapohunda, O.; Ige, A.O.; Ling, J. Artificial Intelligence Potential for Net Zero Sustainability: Current Evidence and Prospects. *Next Sustain.* **2024**, *4*, 100041. [CrossRef]
79. Gonçalves, A.C.R.; Costoya, X.; Nieto, R.; Liberato, M.L.R. Extreme Weather Events on Energy Systems: A Comprehensive Review on Impacts, Mitigation, and Adaptation Measures. *Sustain. Energy Res.* **2024**, *11*, 4. [CrossRef]
80. Hassan, Q.; Algburi, S.; Sameen, A.Z.; Salman, H.M.; Jaszczur, M. A Review of Hybrid Renewable Energy Systems: Solar and Wind-Powered Solutions: Challenges, Opportunities, and Policy Implications. *Results Eng.* **2023**, *20*, 101621. [CrossRef]
81. Haji-Aghajany, S.; Rohm, W.; Lipinski, P.; Kryza, M. Beyond the Horizon: A Critical Analysis of AI-Based Weather Forecasting Models. *ESS Open Arch.* **2024**. [CrossRef]
82. Aderibigbe, A.O.; Ani, E.C.; Ohenhen, P.E.; Ohalete, N.C.; Daraojimba, D.O. Enhancing Energy Efficiency with AI: A Review of Machine Learning Models in Electricity Demand Forecasting. *Eng. Sci. Technol. J.* **2023**, *4*, 341–356. [CrossRef]
83. Antonopoulos, I.; Robu, V.; Couraud, B.; Kirli, D.; Norbu, S.; Kiprakis, A.; Flynn, D.; Elizondo-Gonzalez, S.; Wattam, S. Artificial Intelligence and Machine Learning Approaches to Energy Demand-Side Response: A Systematic Review. *Renew. Sustain. Energy Rev.* **2020**, *130*, 109899. [CrossRef]
84. Ragupathi, C.; Dhanasekaran, S.; Vijayalakshmi, N.; Salau, A.O. Prediction of Electricity Consumption Using an Innovative Deep Energy Predictor Model for Enhanced Accuracy and Efficiency. *Energy Rep.* **2024**, *12*, 5320–5337. [CrossRef]
85. Ibegbulam, C.M.; Aigbovbiosa, O.J.; Olowonubi, J.A.; Fatounde, S.A. Role of Artificial Intelligence in Electrification of Africa. *Eng. Sci. Technol. J.* **2023**, *4*, 456–472. [CrossRef]
86. Hamdan, A.; Ibekwe, K.I.; Etukudoh, E.A.; Umoh, A.A.; Ilojianya, V.I. AI and Machine Learning in Climate Change Research: A Review of Predictive Models and Environmental Impact. *World J. Adv. Res. Rev.* **2024**, *21*, 1999–2008. [CrossRef]
87. Sebestyén, V.; Czvetkó, T.; Abonyi, J. The Applicability of Big Data in Climate Change Research: The Importance of System of Systems Thinking. *Front. Environ. Sci.* **2021**, *9*, 619092. [CrossRef]
88. Niri, A.J.; Poelzer, G.A.; Zhang, S.E.; Rosenkranz, J.; Pettersson, M.; Ghorbani, Y. Sustainability Challenges throughout the Electric Vehicle Battery Value Chain. *Renew. Sustain. Energy Rev.* **2024**, *191*, 114176. [CrossRef]
89. Alkhalidi, A.; Khawaja, M.K.; Ismail, S.M. Solid-State Batteries, Their Future in the Energy Storage and Electric Vehicles Market. *Sci. Talks* **2024**, *11*, 100382. [CrossRef]
90. Olabi, A.G.; Allam, M.A.; Abdelkareem, M.A.; Deepa, T.D.; Alami, A.H.; Abbas, Q.; Alkhalidi, A.; Sayed, E.T. Redox Flow Batteries: Recent Development in Main Components, Emerging Technologies, Diagnostic Techniques, Large-Scale Applications, and Challenges and Barriers. *Batteries* **2023**, *9*, 409. [CrossRef]
91. Elalfy, D.A.; Gouda, E.; Kotb, M.F.; Bureš, V.; Sedhom, B.E. Comprehensive Review of Energy Storage Systems Technologies, Objectives, Challenges, and Future Trends. *Energy Strategy Rev.* **2024**, *54*, 101482. [CrossRef]
92. Yang, Y.; Wu, Z.; Yao, J.; Guo, T.; Yang, F.; Zhang, Z.; Ren, J.; Jiang, L.; Li, B. An Overview of Application-Oriented Multifunctional Large-Scale Stationary Battery and Hydrogen Hybrid Energy Storage System. *Energy Rev.* **2024**, *3*, 100068. [CrossRef]
93. Wang, Z.; Zhang, X.; Rezazadeh, A. Hydrogen Fuel and Electricity Generation from a New Hybrid Energy System Based on Wind and Solar Energies and Alkaline Fuel Cell. *Energy Rep.* **2021**, *7*, 2594–2604. [CrossRef]
94. Ren, D.; Lu, L.; Hua, R.; Zhu, G.; Liu, X.; Mao, Y.; Rui, X.; Wang, S.; Zhao, B.; Cui, H.; et al. Challenges and Opportunities of Practical Sulfide-Based All-Solid-State Batteries. *eTransportation* **2023**, *18*, 100272. [CrossRef]
95. Nyangon, J.; Darekar, A. Advancements in Hydrogen Energy Systems: A Review of Levelized Costs, Financial Incentives and Technological Innovations. *Innov. Green Dev.* **2024**, *3*, 100149. [CrossRef]
96. Madureira, A.G.; Pereira, J.C.; Gil, N.J.; Lopes, J.A.P.; Korres, G.N.; Hatziargyriou, N.D. Advanced Control and Management Functionalities for Multi-Microgrids. *Eur. Trans. Electr. Power* **2011**, *21*, 1159–1177. [CrossRef]
97. Safari, A.; Daneshvar, M.; Anvari-Moghaddam, A. Energy Intelligence: A Systematic Review of Artificial Intelligence for Energy Management. *Appl. Sci.* **2024**, *14*, 11112. [CrossRef]
98. Birleanu, F.G.; Bizon, N. Control and Protection of the Smart Microgrids Using Internet of Things: Technologies, Architecture and Applications. In *Microgrid Architectures, Control and Protection Methods*; Mahdavi Tabatabaei, N., Kabalci, E., Bizon, N., Eds.; Springer International Publishing: Cham, Switzerland, 2020; pp. 749–770. ISBN 978-3-030-23723-3.
99. Gawusu, S.; Zhang, X.; Ahmed, A.; Jamatutu, S.A.; Miensah, E.D.; Amadu, A.A.; Osei, F.A.J. Renewable Energy Sources from the Perspective of Blockchain Integration: From Theory to Application. *Sustain. Energy Technol. Assess.* **2022**, *52*, 102108. [CrossRef]

100. Cui, M.; Feng, T.; Wang, H. How Can Blockchain Be Integrated into Renewable Energy?—A Bibliometric-Based Analysis. *Energy Strategy Rev.* **2023**, *50*, 101207. [CrossRef]
101. Trivedi, R.; Khadem, S. Implementation of Artificial Intelligence Techniques in Microgrid Control Environment: Current Progress and Future Scopes. *Energy AI* **2022**, *8*, 100147. [CrossRef]
102. Li, J.; Ma, S.; Qu, Y.; Wang, J. The Impact of Artificial Intelligence on Firms' Energy and Resource Efficiency: Empirical Evidence from China. *Resour. Policy* **2023**, *82*, 103507. [CrossRef]
103. Egunjobi, O.O.; Gomes, A.; Egwim, C.N.; Morais, H. A Systematic Review of Blockchain for Energy Applications. *e-Prime—Adv. Electr. Eng. Electron. Energy* **2024**, *9*, 100751. [CrossRef]
104. Mahmood, M.; Chowdhury, P.; Yeassin, R.; Hasan, M.; Ahmad, T.; Chowdhury, N.-U.-R. Impacts of Digitalization on Smart Grids, Renewable Energy, and Demand Response: An Updated Review of Current Applications. *Energy Convers. Manag. X* **2024**, *24*, 100790. [CrossRef]
105. Majeed, Y.; Khan, M.U.; Waseem, M.; Zahid, U.; Mahmood, F.; Majeed, F.; Sultan, M.; Raza, A. Renewable Energy as an Alternative Source for Energy Management in Agriculture. *Energy Rep.* **2023**, *10*, 344–359. [CrossRef]
106. Jufri, F.H.; Aryani, D.R.; Garniwa, I.; Sudiarto, B. Optimal Battery Energy Storage Dispatch Strategy for Small-Scale Isolated Hybrid Renewable Energy System with Different Load Profile Patterns. *Energies* **2021**, *14*, 3139. [CrossRef]
107. Aghmadi, A.; Mohammed, O.A. Energy Storage Systems: Technologies and High-Power Applications. *Batteries* **2024**, *10*, 141. [CrossRef]
108. Sayeed, F.; Hanumanthakari, S.; Oommen, S.; Anitha, G.; Hemavathi, S.; Pundir, A.K.S.; Sudhakar, M.; Sathyamurthy, R.; Mohanavel, V. A Novel and Comprehensive Mechanism for the Energy Management of a Hybrid Micro-Grid System. *Energy Rep.* **2022**, *8*, 847–862. [CrossRef]
109. Zhou, X.; Mansouri, S.A.; Rezaee Jordehi, A.; Tostado-Véliz, M.; Jurado, F. A Three-Stage Mechanism for Flexibility-Oriented Energy Management of Renewable-Based Community Microgrids with High Penetration of Smart Homes and Electric Vehicles. *Sustain. Cities Soc.* **2023**, *99*, 104946. [CrossRef]
110. Panda, A.; Dauda, A.K.; Chua, H.; Tan, R.R.; Aviso, K.B. Recent Advances in the Integration of Renewable Energy Sources and Storage Facilities with Hybrid Power Systems. *Clean. Eng. Technol.* **2023**, *12*, 100598. [CrossRef]
111. Pandiyan, P.; Saravanan, S.; Usha, K.; Kannadasan, R.; Alsharif, M.H.; Kim, M.-K. Technological Advancements toward Smart Energy Management in Smart Cities. *Energy Rep.* **2023**, *10*, 648–677. [CrossRef]
112. Obaideen, K.; Albasha, L.; Iqbal, U.; Mir, H. Wireless Power Transfer: Applications, Challenges, Barriers, and the Role of AI in Achieving Sustainable Development Goals—A Bibliometric Analysis. *Energy Strategy Rev.* **2024**, *53*, 101376. [CrossRef]
113. Čábelková, I.; Strielkowski, W.; Wende, F.-D.; Krayneva, R. Factors Influencing the Threats for Urban Energy Networks: The Inhabitants' Point of View. *Energies* **2020**, *13*, 5659. [CrossRef]
114. Rezvani, S.M.; Falcão, M.J.; Komljenovic, D.; de Almeida, N.M. A Systematic Literature Review on Urban Resilience Enabled with Asset and Disaster Risk Management Approaches and GIS-Based Decision Support Tools. *Appl. Sci.* **2023**, *13*, 2223. [CrossRef]
115. Almaleh, A.; Tipper, D.; Al-Gahtani, S.F.; El-Sehiemy, R. A Novel Model for Enhancing the Resilience of Smart MicroGrids' Critical Infrastructures with Multi-Criteria Decision Techniques. *Appl. Sci.* **2022**, *12*, 9756. [CrossRef]
116. Hervás-Zaragoza, J.; Colmenar-Santos, A.; Rosales-Asensio, E.; Colmenar-Fernández, L. Microgrids as a Mechanism for Improving Energy Resilience during Grid Outages: A Post COVID-19 Case Study for Hospitals. *Renew. Energy* **2022**, *199*, 308–319. [CrossRef]
117. Yu, H.; Niu, S.; Zhang, Y.; Jian, L. An Integrated and Reconfigurable Hybrid AC/DC Microgrid Architecture with Autonomous Power Flow Control for Nearly/Net Zero Energy Buildings. *Appl. Energy* **2020**, *263*, 114610. [CrossRef]
118. Punitha, S.; Subramaniam, N.P.; Vimal Raj, P.A.D. A Comprehensive Review of Microgrid Challenges in Architectures, Mitigation Approaches, and Future Directions. *J. Electr. Syst. Inf. Technol.* **2024**, *11*, 60. [CrossRef]
119. Zhang, Z.; Li, X.; Li, Y.; Hu, G.; Wang, X.; Zhang, G.; Tao, H. Modularity, Reconfigurability, and Autonomy for the Future in Spacecraft: A Review. *Chin. J. Aeronaut.* **2023**, *36*, 282–315. [CrossRef]
120. Khare, V.; Chaturvedi, P. Design, Control, Reliability, Economic and Energy Management of Microgrid: A Review. *e-Prime—Adv. Electr. Eng. Electron. Energy* **2023**, *5*, 100239. [CrossRef]
121. Caputo, C.; Cardin, M.-A.; Ge, P.; Teng, F.; Korre, A.; Antonio del Rio Chanona, E. Design and Planning of Flexible Mobile Micro-Grids Using Deep Reinforcement Learning. *Appl. Energy* **2023**, *335*, 120707. [CrossRef]
122. Li, Z.; Shahidehpour, M.; Aminifar, F.; Alabdulwahab, A.; Al-Turki, Y. Networked Microgrids for Enhancing the Power System Resilience. *Proc. IEEE* **2017**, *105*, 1289–1310. [CrossRef]
123. Galvan, E.; Mandal, P.; Sang, Y. Networked Microgrids with Roof-Top Solar PV and Battery Energy Storage to Improve Distribution Grids Resilience to Natural Disasters. *Int. J. Electr. Power Energy Syst.* **2020**, *123*, 106239. [CrossRef]
124. Hamidieh, M.; Ghassemi, M. Microgrids and Resilience: A Review. *IEEE Access* **2022**, *10*, 106059–106080. [CrossRef]
125. Parhizi, S.; Lotfi, H.; Khodaei, A.; Bahramirad, S. State of the Art in Research on Microgrids: A Review. *IEEE Access* **2015**, *3*, 890–925. [CrossRef]

126. Gan, L.K.; Hussain, A.; Howey, D.A.; Kim, H.-M. Limitations in Energy Management Systems: A Case Study for Resilient Interconnected Microgrids. *IEEE Trans. Smart Grid* **2019**, *10*, 5675–5685. [CrossRef]
127. Powell, J.; McCafferty-Leroux, A.; Hilal, W.; Gadsden, S.A. Smart Grids: A Comprehensive Survey of Challenges, Industry Applications, and Future Trends. *Energy Rep.* **2024**, *11*, 5760–5785. [CrossRef]
128. Bari, L.F.; Ahmed, I.; Ahamed, R.; Zihan, T.A.; Sharmin, S.; Pranto, A.H.; Islam, M.R. Potential Use of Artificial Intelligence (AI) in Disaster Risk and Emergency Health Management: A Critical Appraisal on Environmental Health. *Environ. Health Insights* **2023**, *17*, 11786302231217808. [CrossRef]
129. Marqusee, J.; Jenket, D. Reliability of Emergency and Standby Diesel Generators: Impact on Energy Resiliency Solutions. *Appl. Energy* **2020**, *268*, 114918. [CrossRef]
130. Damaševičius, R.; Bacanin, N.; Misra, S. From Sensors to Safety: Internet of Emergency Services (IoES) for Emergency Response and Disaster Management. *J. Sens. Actuator Netw.* **2023**, *12*, 41. [CrossRef]
131. Dai, D.; Bo, M.; Ren, X.; Dai, K. Application and Exploration of Artificial Intelligence Technology in Urban Ecosystem-Based Disaster Risk Reduction: A Scoping Review. *Ecol. Indic.* **2024**, *158*, 111565. [CrossRef]
132. Ghaffarian, S.; Taghikhah, F.R.; Maier, H.R. Explainable Artificial Intelligence in Disaster Risk Management: Achievements and Prospective Futures. *Int. J. Disaster Risk Reduct.* **2023**, *98*, 104123. [CrossRef]
133. Biswal, B.; Deb, S.; Datta, S.; Ustun, T.S.; Cali, U. Review on Smart Grid Load Forecasting for Smart Energy Management Using Machine Learning and Deep Learning Techniques. *Energy Rep.* **2024**, *12*, 3654–3670. [CrossRef]
134. Onwusinkwue, S.; Osasona, F.; Ahmad, I.A.I.; Anyanwu, A.C.; Dawodu, S.O.; Obi, O.C.; Hamdan, A. Artificial Intelligence (AI) in Renewable Energy: A Review of Predictive Maintenance and Energy Optimization. *World J. Adv. Res. Rev.* **2024**, *21*, 2487–2499. [CrossRef]
135. Albahri, A.S.; Khaleel, Y.L.; Habeeb, M.A.; Ismael, R.D.; Hameed, Q.A.; Deveci, M.; Homod, R.Z.; Albahri, O.S.; Alamoodi, A.H.; Alzubaidi, L. A Systematic Review of Trustworthy Artificial Intelligence Applications in Natural Disasters. *Comput. Electr. Eng.* **2024**, *118*, 109409. [CrossRef]
136. Javanroodi, K.; Perera, A.T.D.; Hong, T.; Nik, V.M. Designing Climate Resilient Energy Systems in Complex Urban Areas Considering Urban Morphology: A Technical Review. *Adv. Appl. Energy* **2023**, *12*, 100155. [CrossRef]
137. Kalair, A.; Jamei, E.; Seyedmahmoudian, M.; Mekhilef, S.; Abas, N. Building the Future: Integrating Phase Change Materials in Network of Nanogrids (NoN). *Energies* **2024**, *17*, 5862. [CrossRef]
138. Ohenhen, P.E.; Chidolue, O.; Umoh, A.A.; Ngozichukwu, B.; Fafure, A.V.; Ilojianya, V.I.; Ibekwe, K.I. Sustainable Cooling Solutions for Electronics: A Comprehensive Review: Investigating the Latest Techniques and Materials, Their Effectiveness in Mechanical Applications, and Associated Environmental Benefits. *World J. Adv. Res. Rev.* **2024**, *21*, 957–972. [CrossRef]
139. Rashid, F.L.; Al-Obaidi, M.A.; Dulaimi, A.; Bernardo, L.F.A.; Eleiwi, M.A.; Mahood, H.B.; Hashim, A. A Review of Recent Improvements, Developments, Effects, and Challenges on Using Phase-Change Materials in Concrete for Thermal Energy Storage and Release. *J. Compos. Sci.* **2023**, *7*, 352. [CrossRef]
140. Said, Z.; Pandey, A.K.; Tiwari, A.K.; Kalidasan, B.; Jamil, F.; Thakur, A.K.; Tyagi, V.V.; Sarı, A.; Ali, H.M. Nano-Enhanced Phase Change Materials: Fundamentals and Applications. *Prog. Energy Combust. Sci.* **2024**, *104*, 101162. [CrossRef]
141. Xu, L.; Zhu, M.; Zhao, J.; Chen, M.; Shi, M. The Utilization of Shape Memory Alloy as a Reinforcing Material in Building Structures: A Review. *Materials* **2024**, *17*, 2634. [CrossRef]
142. Ajirotutu, R.O.; Adeyemi, A.B.; Ifechukwu, G.-O.; Iwuanyanwu, O.; Ohakawa, T.C.; Garba, B.M.P. Future Cities and Sustainable Development: Integrating Renewable Energy, Advanced Materials, and Civil Engineering for Urban Resilience. *Magna Sci. Adv. Res. Rev.* **2024**, *12*, 235–250. [CrossRef]
143. Azmeer, A.; Tahir, F.; Al-Ghamdi, S.G. Progress on Green Infrastructure for Urban Cooling: Evaluating Techniques, Design Strategies, and Benefits. *Urban Clim.* **2024**, *56*, 102077. [CrossRef]
144. Ang, T.-Z.; Salem, M.; Kamarol, M.; Das, H.S.; Nazari, M.A.; Prabaharan, N. A Comprehensive Study of Renewable Energy Sources: Classifications, Challenges and Suggestions. *Energy Strategy Rev.* **2022**, *43*, 100939. [CrossRef]
145. Kapucu, N.; Ge, Y.; Rott, E.; Isgandar, H. Urban Resilience: Multidimensional Perspectives, Challenges and Prospects for Future Research. *Urban Gov.* **2024**, *4*, 162–179. [CrossRef]
146. Bose, D.; Bhattacharya, R.; Kaur, T.; Pandya, R.; Sarkar, A.; Ray, A.; Mondal, S.; Mondal, A.; Ghosh, P.; Chemudupati, R.I. Innovative Approaches for Carbon Capture and Storage as Crucial Measures for Emission Reduction within Industrial Sectors. *Carbon Capture Sci. Technol.* **2024**, *12*, 100238. [CrossRef]
147. Mohanty, A.; Ramasamy, A.K.; Verayiah, R.; Bastia, S.; Dash, S.S.; Cuce, E.; Khan, T.M.Y.; Soudagar, M.E.M. Power System Resilience and Strategies for a Sustainable Infrastructure: A Review. *Alex. Eng. J.* **2024**, *105*, 261–279. [CrossRef]
148. Mbungu, N.T.; Naidoo, R.M.; Bansal, R.C.; Siti, M.W.; Tungadio, D.H. An Overview of Renewable Energy Resources and Grid Integration for Commercial Building Applications. *J. Energy Storage* **2020**, *29*, 101385. [CrossRef]
149. Lakshmi Narayanan, R.G.; Ibe, O.C. A Joint Network for Disaster Recovery and Search and Rescue Operations. *Comput. Netw.* **2012**, *56*, 3347–3373. [CrossRef]

150. Linardos, V.; Drakaki, M.; Tzionas, P.; Karnavas, Y.L. Machine Learning in Disaster Management: Recent Developments in Methods and Applications. *Mach. Learn. Knowl. Extr.* **2022**, *4*, 446–473. [CrossRef]
151. Thirumalai, M.; Hariharan, R.; Yuvaraj, T.; Prabaharan, N. Optimizing Distribution System Resilience in Extreme Weather Using Prosumer-Centric Microgrids with Integrated Distributed Energy Resources and Battery Electric Vehicles. *Sustainability* **2024**, *16*, 2379. [CrossRef]
152. Wang, Y.; Rousis, A.O.; Strbac, G. On Microgrids and Resilience: A Comprehensive Review on Modeling and Operational Strategies. *Renew. Sustain. Energy Rev.* **2020**, *134*, 110313. [CrossRef]
153. Poland, B.; Gloger, A.; Morgan, G.T.; Lach, N.; Jackson, S.F.; Urban, R.; Rolston, I. A Connected Community Approach: Citizens and Formal Institutions Working Together to Build Community-Centred Resilience. *Int. J. Environ. Res. Public Health* **2021**, *18*, 10175. [CrossRef] [PubMed]
154. Phua, S.Z.; Hofmeister, M.; Tsai, Y.-K.; Peppard, O.; Lee, K.F.; Courtney, S.; Mosbach, S.; Akroyd, J.; Kraft, M. Fostering Urban Resilience and Accessibility in Cities: A Dynamic Knowledge Graph Approach. *Sustain. Cities Soc.* **2024**, *113*, 105708. [CrossRef]
155. Norouzi, F.; Hoppe, T.; Kamp, L.M.; Manktelow, C.; Bauer, P. Diagnosis of the Implementation of Smart Grid Innovation in The Netherlands and Corrective Actions. *Renew. Sustain. Energy Rev.* **2023**, *175*, 113185. [CrossRef]
156. Brown, D.; Hall, S.; Davis, M.E. What Is Prosumerism for? Exploring the Normative Dimensions of Decentralised Energy Transitions. *Energy Res. Soc. Sci.* **2020**, *66*, 101475. [CrossRef]
157. Wolsink, M. Distributed Energy Systems as Common Goods: Socio-Political Acceptance of Renewables in Intelligent Microgrids. *Renew. Sustain. Energy Rev.* **2020**, *127*, 109841. [CrossRef]
158. Mauger, R. Defining Microgrids: From Technology to Law. *J. Energy Nat. Resour. Law* **2023**, *41*, 287–304. [CrossRef]
159. Wouters, C. Towards a Regulatory Framework for Microgrids—The Singapore Experience. *Sustain. Cities Soc.* **2015**, *15*, 22–32. [CrossRef]
160. Bellido, M.H.; Rosa, L.P.; Pereira, A.O.; Falcão, D.M.; Ribeiro, S.K. Barriers, Challenges and Opportunities for Microgrid Implementation: The Case of Federal University of Rio de Janeiro. *J. Clean. Prod.* **2018**, *188*, 203–216. [CrossRef]
161. Nyarko, K.; Whale, J.; Urmee, T. Drivers and Challenges of Off-Grid Renewable Energy-Based Projects in West Africa: A Review. *Heliyon* **2023**, *9*, e16710. [CrossRef]
162. Eklund, M.; Khalilpour, K.; Voinov, A.; Hossain, M.J. Community Microgrids: A Decision Framework Integrating Social Capital with Business Models for Improved Resiliency. *Appl. Energy* **2024**, *367*, 123458. [CrossRef]
163. Faia, R.; Lezama, F.; Soares, J.; Pinto, T.; Vale, Z. Local Electricity Markets: A Review on Benefits, Barriers, Current Trends and Future Perspectives. *Renew. Sustain. Energy Rev.* **2024**, *190*, 114006. [CrossRef]
164. Glemarec, Y. Financing Off-Grid Sustainable Energy Access for the Poor. *Energy Policy* **2012**, *47*, 87–93. [CrossRef]
165. Wu, H.; Carroll, J.; Denny, E. Harnessing Citizen Investment in Community-Based Energy Initiatives: A Discrete Choice Experiment across Ten European Countries. *Energy Res. Soc. Sci.* **2022**, *89*, 102552. [CrossRef]
166. Ali, A.; Li, W.; Hussain, R.; He, X.; Williams, B.W.; Memon, A.H. Overview of Current Microgrid Policies, Incentives and Barriers in the European Union, United States and China. *Sustainability* **2017**, *9*, 1146. [CrossRef]
167. Sun, B.; Li, M.; Wang, F.; Xie, J. An Incentive Mechanism to Promote Residential Renewable Energy Consumption in China's Electricity Retail Market: A Two-Level Stackelberg Game Approach. *Energy* **2023**, *269*, 126861. [CrossRef]
168. Zerka, A.; Ouassaid, M.; Maaroufi, M.; Rabeh, R. Towards Net Zero: Comprehensive Approach for Voluntary Carbon Trading among Microgrids. *Heliyon* **2024**, *10*, e39106. [CrossRef]
169. Tzani, D.; Stavrakas, V.; Santini, M.; Thomas, S.; Rosenow, J.; Flamos, A. Pioneering a Performance-Based Future for Energy Efficiency: Lessons Learnt from a Comparative Review Analysis of Pay-for-Performance Programmes. *Renew. Sustain. Energy Rev.* **2022**, *158*, 112162. [CrossRef]
170. Polzin, F.; Egli, F.; Steffen, B.; Schmidt, T.S. How Do Policies Mobilize Private Finance for Renewable Energy?—A Systematic Review with an Investor Perspective. *Appl. Energy* **2019**, *236*, 1249–1268. [CrossRef]
171. Agupugo, C.P.; Ajayi, A.O.; Nwanevu, C.; Oladipo, S.S. Policy and Regulatory Framework Supporting Renewable Energy Microgrids and Energy Storage Systems. *Eng. Sci. Technol. J.* **2024**, *5*, 2589–2615. [CrossRef]
172. Nwanevu, C.; Oladipo, S.S.; Ajayi, A.O. Designing Effective Policy Frameworks for the Implementation of Microgrids in Developing Countries: Opportunities, Challenges and Pathways to Sustainable Energy Access. *World J. Adv. Res. Rev.* **2024**, *24*, 1279–1294. [CrossRef]