

Review

The Future Design of Smart Energy Systems with Energy Flexumers: A Constructive Literature Review

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Abstract: From powering our homes to driving our economies, energy lies at the heart of humanity's complex challenges in the modern era. This paper reviews the evolution of smart energy systems, examining their technological advancements and societal implications while proposing a future design framework emphasizing four key pillars: holistic resource optimization, adaptive intelligence, environmental harmony, and human-centered design. While they offer numerous benefits, such as enhanced energy efficiency and reduced carbon emissions, smart energy systems also face challenges. These include cybersecurity risks, the complexity of integrating diverse energy sources seamlessly, high upfront costs, and potential compatibility issues arising from evolving technologies. Overcoming these challenges will be crucial for unleashing the full potential of smart energy systems and facilitating their global adoption. Abundant opportunities for further research and development exist in this domain, awaiting exploration and advancement.

Keywords: smart energy systems; energy flexumers; smart grids; future design; renewable energy; net-zero emission; sustainability



Citation: Hu, J.-L.; Bui, N.H.B. The Future Design of Smart Energy Systems with Energy Flexumers: A Constructive Literature Review. *Energies* **2024**, *17*, 2039. <https://doi.org/10.3390/en17092039>

Academic Editor: Peter V. Schaeffer

Received: 27 March 2024

Revised: 19 April 2024

Accepted: 22 April 2024

Published: 25 April 2024



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1. Introduction

Energy stands as a critical determinant shaping 21st century challenges, given its direct and indirect impact on key pillars of humanity. Conventional fossil fuels have long served as the foundation of the global energy landscape. Nevertheless, our widespread dependence on fossil energy, without consideration of the associated consequences, presents substantial environmental and sustainability concerns. First, burning fossil fuels is necessary to extract energy from them, but this process comes with a host of problems. Combustion leads to issues like greenhouse gas (GHG) emissions, air and water pollution, and land degradation. Of these, global warming, caused by GHG emissions, leads to significant climate changes, which have adversely affected human societies [1]. Second, humanity is facing the challenge of depleting fossil energy sources [2,3]. Non-renewable fossil fuels cannot sustainably fulfill the rising energy needs of human societies over time. These challenges are approaching swiftly. In this current situation of accelerating climate change, resource exhaustion, and escalating energy demands, the need for innovative approaches to energy production, distribution, and consumption has never been more urgent.

A significant issue lies in the fact that while future generations may be significantly impacted by present actions, they lack the ability to negotiate with the current generation [4]. Therefore, the question arises: “What measures can be taken to overcome this problem?” Within this context, the concepts of ‘Ministry for the Future’ and ‘Future Design’ represent an innovative and forward-thinking approach, acting as a catalyst for addressing intergenerational equity and sustainability in our energy landscape. The Ministry of the Future refers to a group of present-day advocates working tirelessly to secure a brighter future for generations to come. The concept was created and implemented by the Iroquois [5]. The Iroquois people were required to think ahead to the well-being of their next seven generations when making decisions, as stated in Law 28 of their Constitution [6]. Essentially, the

Iroquois placed great weight on future descendants, addressing their needs as present-day realities prior to reaching decisions. Their aim was a 'Future Design' of structurally stable systems and the development of resilience, resulting from acknowledging the importance of future generations and recognizing such foresight. This concept was later echoed in Kim Stanley Robinson's novel, 'The Ministry for the Future'. At its core, the Ministry for the Future represents the idea of planning ahead, thinking long-term, and being responsible for the future. It is all about protecting the well-being of future generations.

Within the framework of the Ministry for the Future, future design for better energy systems fulfills a pivotal function in orchestrating the shift towards a more equitable, resilient, and renewable energy paradigm. In an era marked by escalating energy demands and rising environmental concerns, fossil energy no longer suffices as a solution due to its unsustainability. Given this situation, the Paris Agreement was adopted in 2015 by 196 Parties at the UN Climate Change Conference (COP21) in Paris, France, as a legally binding global treaty on climate change. It requires all governments to reduce emissions by 45% by 2030 and achieve net zero emissions by 2050 [7]. As a result, continuous efforts are being made to become more energy-efficient and mitigate emission levels. Renewable energies (e.g., solar energy, ocean energy, wind power, biomass), as viable alternatives, have gradually replaced fossil energy in energy generation. Nonetheless, the inconsistent nature of renewable energies, their susceptibility to external factors [8,9], and fluctuations in energy demand over time impose new obstacles [10]. Hence, it is crucial to find a solution to maintain the balance between energy supply and demand effectively. Reliable and innovative approaches and frameworks are critically required to establish sustainable energy systems in the upcoming years [11].

Consequently, the emergence of the 'smart grid' concept has presented a digital-era solution to facilitate more effective integration of fluctuating renewable energies. In general, a smart grid embodies an electricity delivery system that utilizes intelligent communication technology, thereby optimizing energy usage and reducing expenses [12]. In contrast to 'old' grids, which are characterized by unidirectional power flow, centralized power dispatch, and limited or no consumer involvement and end-to-end communication, smart grids feature bidirectional power flow, inclusive access to all network users, and the ability to meet customers' demands and adapt to changes [13]. Despite the need for holistic management of various energy sectors to optimize system performance and achieve synergies between the sectors [14–17], previous studies have predominantly concentrated on the electricity sector when it comes to smart grids. Integrating all energy sectors helps identify appropriate solutions to current challenges, and smart grids should be considered in conjunction with the broader energy landscape [18,19].

The emergence of 'smart energy' appears to have been influenced by the concept of a 'smarter planet', originally put forth by the International Business Machines Corporation (IBM) at the Council of Foreign Relations in New York City, NY, USA, in 2008. IBM's chief executive, Samuel J. Palmisano, outlined its vision for a smarter planet, to leverage technological and computational innovations to develop an intelligent integrated system that enhances power, water, food, transportation, and healthcare systems [20,21]. Accordingly, the strategic research project 'Coherent Energy and Environmental System Analysis' (CEESA) proposed the concept of 'Smart Energy Systems' in 2011 [22]. Subsequently, the academic literature started to acknowledge this in 2012 [18], and a formal definition was established in 2014 [23]. At its core, a smart energy system refers to an economical, secure, and sustainable energy system wherein renewable energy generation, distribution, and consumption are harmoniously integrated and managed via innovative facilitative technologies, energy services, and engaging users [23,24]. Bačeković and Østergaard [25] have also suggested that a smart energy system outweighs a traditional non-integrated system in terms of power production. The idea has also been employed for not only general [26,27] but also local, national, and cross-border regional energy system modeling, as well as transitional pathways [20,28–34]. The evolution of smart energy systems emerges as a beacon of hope, promising transformative solutions for achieving 100% renewable energy

(RE100) [23,29,30,32,33,35–38]. The exploration of applications across various sectors has also been undertaken, examining concepts such as smart energy meters, transportation, green buildings, and smart cities [31,38–41].

Figure 1 illustrates the comparison between current and future energy systems, showing the transition toward sustainability. Compared to the existing energy system, which heavily depends on conventional energy sources, has limited integration of renewable energy sources, operates on centralized power grids, maintains sector separation, exhibits rigidity, and results in negative environmental impact, the smart energy system presents a noticeable contrast. The smart energy system emphasizes holistic resource optimization, adopts human-centered design principles through decentralization and sector interconnection, employs adaptive intelligence, and aims for future environmental harmony. By integrating various energy applications and optimizing resource utilization, smart energy systems not only address current energy challenges, but also pave the way for a sustainable future.

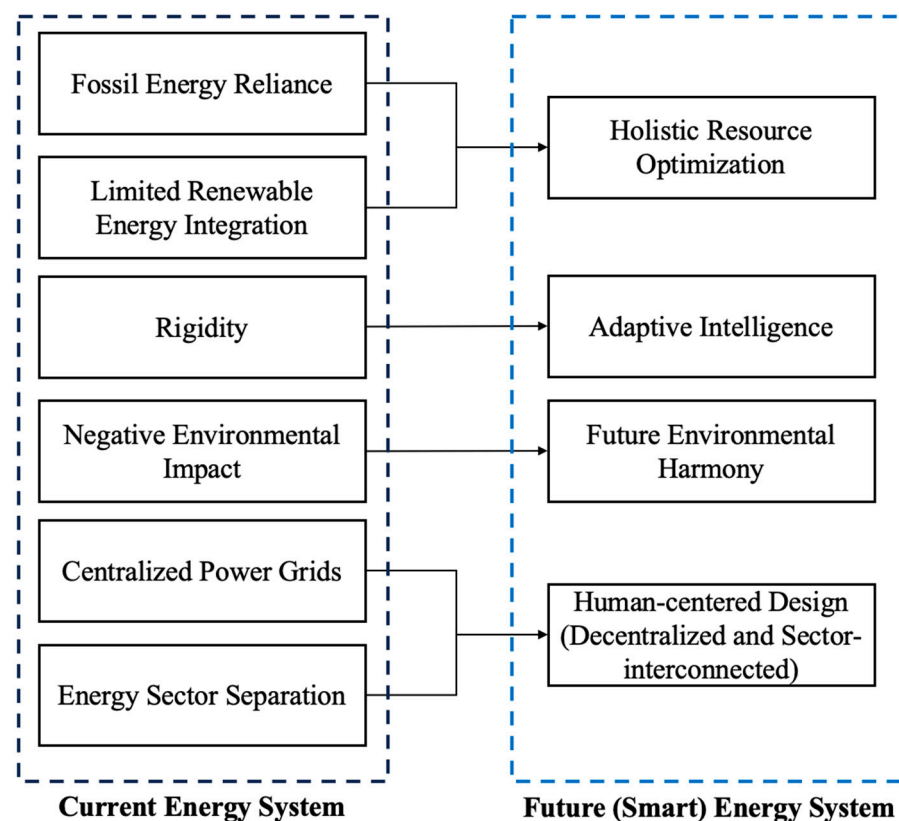


Figure 1. Transition towards sustainability: comparison between current energy system and smart energy system.

As humanity stands at the nexus of technological innovation and sustainability imperatives, the invention and deployment of intelligent energy systems is instrumental in defining the future landscape of society and economy. This paper conducts a literature review focusing on the advancement of smart energy systems, their human socio-economic aspects, and their role in fostering a sustainable and resilient future. Utilizing Google Scholar as the primary search engine, we identified relevant academic and technical documents and prioritized those that offered social, economic, and managerial insights for further detailed analysis and summarization. In addition to ‘future design’ and ‘smart energy systems’ as the main search keywords, other keywords included ‘holistic resource optimization’, ‘human-centered design’, ‘adaptive intelligence’, and ‘future environmental harmony’. Figure 2 shows the conceptual framework derived from the literature review from future design viewpoints and involves the following parts: holistic resource optimiza-

tion, adaptive intelligence, future environmental harmony, and human-centered design. Ultimately, conclusions and recommendations for future research are provided.

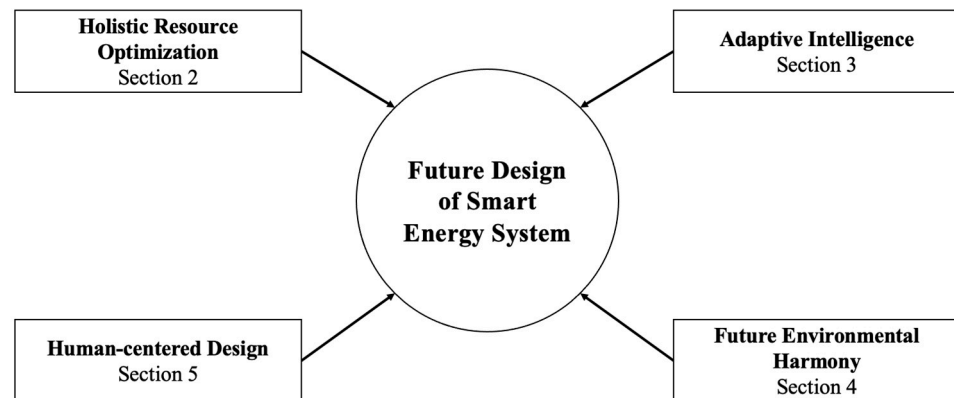


Figure 2. Conceptual framework derived from the literature review with future design viewpoints.

2. Holistic Resource Optimization

The process of optimizing energy systems for efficiency and sustainability has traditionally focused on isolated aspects, such as generation or consumption. This section advocates for a holistic approach to resource optimization, wherein the interactions between different energy sources are considered in order to achieve a truly sustainable and resilient energy future.

Initially, Dincer and Acar [42] introduced the framework for the ‘smart energy system’, advocating for its comprehensive coverage across every aspect of the energy supply and demand chain. Their conceptualization, known as the ‘3S concept’ (Source–System–Service), has evolved into the current model of smart energy systems. Energy-generating stations, energy transmission and storage infrastructure, smart energy management systems, and end users are the fundamental components of a typical smart energy system [43–45]. Energy-generating stations are responsible for producing energy to meet the diverse energy needs of end users. Energy transmission systems facilitate the transmission of energy from its sources to consumers, while storage systems store surplus-generated energy for later use. Smart energy systems control the entire system and its components. A comprehensive layout of a smart energy system is depicted in Figure 3.

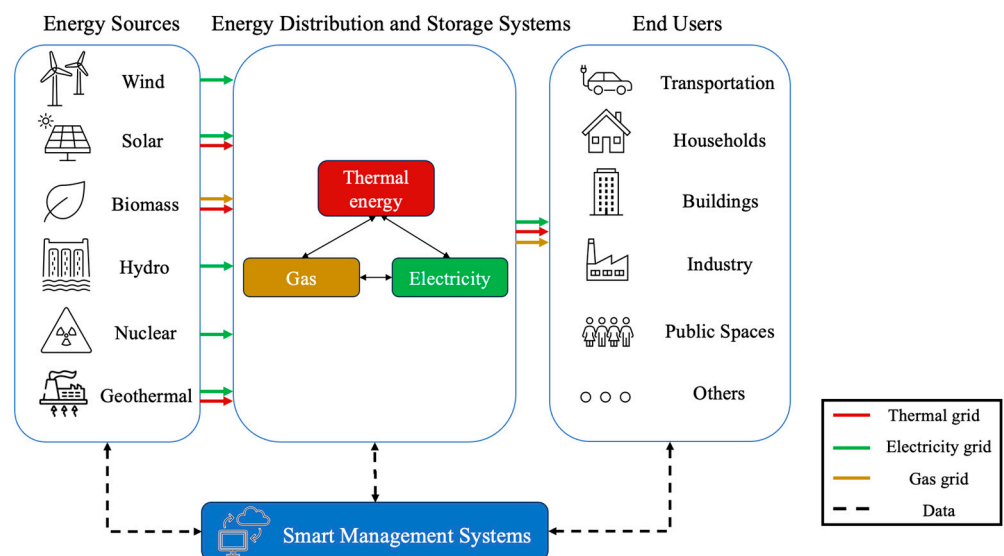


Figure 3. A comprehensive layout of a smart energy system.

The optimization of functions in an energy generation system plays a critical role in holistic resource utilization within a smart energy system. This goes beyond simply maximizing individual generation capacities. Instead, the focus shifts towards coordinating and optimizing the operation of diverse energy sources, such as solar, wind, and biomass [28]. This requires intelligent scheduling algorithms that consider real-time demand, weather forecasts, and variable resource availability [43,45]. By predicting and balancing the output of different sources, the system can minimize dependence on carbon-based fuels and maximize the utilization of renewable resources, ultimately contributing to overall system efficiency and cost-effectiveness. Energy generators are tasked with generating energy to satisfy the varied energy requirements of consumers [12]. Solar, wind, biomass, geothermal, and other alternatives represent currently available renewable energy sources [11–13,44]. Leveraging these sustainable resources for power generation holds significant promise for effectively addressing power supply challenges.

The conversion of primary energy sources into secondary energy forms, including thermal energy, gas, and electricity, is also a task handled by energy generation systems. Photovoltaic (PV) systems (i.e., solar panels), wind turbines, tidal turbines, hydroelectric dams, nuclear reactors, biomass combustion systems, geothermal power plants, and poly-generation units are conventional energy generation devices. Solar energy, given its attributes of abundance, cleanliness, and sustainability, plays a pivotal role in endeavors aimed at combating climate change and shifting towards greener energy alternatives. It can be harnessed for electricity generation using PV panels, where the interaction of light photons with semiconductor materials initiates energy production through the PV effect, or for thermal power across residential, commercial, and industrial applications [46,47]. Another viable renewable source is wind energy, which is generated by harnessing the kinetic energy in moving air masses facilitated by wind turbines with horizontal or vertical axis designs [48]. While horizontal-axis turbines are the workhorses of wind farms, counter-rotating vertical-axis turbines are more favored and suitable for urban environments [49]. Another promising renewable energy source is biomass, which is obtained from leftover organic materials. Biomass can be burned directly or converted into biofuels (e.g., ethanol and biodiesel), solid or liquid fuels, or electricity for deployment in various sectors [50]. Geothermal energy, deriving from the Earth's internal heat, shows great promise as a resource for an extensive variety of sustainable solutions, especially thermal control in smart buildings [51–53]. While its use in electricity production remains somewhat limited, more countries have begun to tap into this extensive energy source to supply heat for residential, commercial, and industrial needs [54].

Despite notable economic advancements and achieving cost parity with conventional carbon-based fuels, renewable energy sources have yet to demonstrate their competitiveness fully. Current energy supply strategies present a joint consumption of both hydrocarbon fuels and renewable energies, as fossil fuels remain essential in the power landscape due to their high energy density and consistent supply, given that they are unaffected by weather conditions or time of day. Fossil energy has served as the backbone of the economy, playing a crucial role in economic growth and global expansion [55–57]. Moreover, the technologies involved in the extraction, refinement, and utilization of fossil fuels have undergone extensive development and refinement over several decades, resulting in high levels of efficiency and reliability across various applications. Technology maturity in the fossil energy sector has led to infrastructure availability and cost competitiveness as compared to renewables. For these reasons, they serve as a supplementary source for renewable energies, ensuring the consistency and efficiency of system operation, mainly due to the intermittent nature of renewables [43,58] and their lower power density [49]. Even so, fossil energy is being gradually phased out due to its unsustainability and depletion, with the proportion of renewables increasing steadily over time to align with sustainability goals.

Energy generation has traditionally primarily relied on large centralized power plants fueled by non-renewables. Research on energy generation systems has increasingly highlighted hybrid benefits compared to single-source configurations in enhancing energy

generation performance and delivering improved environmental and economic outcomes. Most recent research has centered on examining the functionality of hybrid energy systems combining PV and wind technologies, given that solar and wind energies represent the two most viable renewable energy sources. Celik's study [59] indicated that an optimized solar–wind hybrid system offers greater efficiency than either of the individual systems, and emphasized the importance of battery storage capacity. Yang et al. [60] suggested that the combination of solar and wind energy offers highly satisfactory utilization as they complement each other effectively. A study by Diaf et al. [61] examining standalone hybrid photovoltaic (PV)/wind energy systems on Corsica Island suggested that these hybrid systems can help local energy consumers achieve self-sufficiency. Furthermore, these hybrid systems have been found to outperform single-source systems in terms of power reliability, experiencing almost no power outages. The study also pointed out that the levelized cost of energy (LCE) (i.e., the average cost per unit (kWh) produced by a system, determined by dividing the total annualized cost of the system by the total electrical load it serves) is heavily influenced by the quality of renewables available. Consequently, adding controllable energy sources as backup energy sources enhances power-generating efficiency and simultaneously keeps the LCE at a minimum level. Positive complementary attributes between different energy sources were confirmed, resulting in the determination of the practical viability of hybrid systems equipped with highly tuned storage facilities [62–69].

Urban public spaces represent vast, often overlooked areas that hold the potential for energy generation, poised to hold the key to unlocking a more sustainable future. Despite their ubiquity and centrality in urban life, these spaces still need to be explored in terms of their capacity to generate renewable energy. Duivenvoorden et al. [70] pointed out that public spaces are the backbone of a city, guaranteeing the well-being of citizens. They encompass public and private amenities and contribute to overall infrastructure and quality of life. Lu et al. [71] mentioned that taking into account the ability of urban structures to produce energy marks a significant shift in the perspective of resilient cities. If production activities (e.g., renewable energy generation) take place in public spaces, the resulting revenue could potentially be utilized for direct community welfare, thereby subsidizing structure maintenance expenses [72]. Incorporating these concepts into public spaces warrants more thorough research [73]. Ozgun et al. [73] employed a case study approach at Ballast Point Park in Sydney (Australia) to investigate the triple bottom line (TBL) as a design framework, concentrating on the distribution of renewables within public spaces. The results indicated that to create genuinely sustainable environments, designers of public spaces must address all three TBL components, with a specific emphasis on achieving economic sustainability alongside social and environmental sustainability.

Additionally, there exists a compelling opportunity to harness the latent energy potential of urban landscapes with the advent of smart grid technologies. By strategically integrating renewable energy infrastructure within these spaces and seamlessly connecting them to smart grids, cities can unlock a myriad of benefits, especially in enhancing energy security. Zhao et al. [74] introduced a radiofrequency power storage and energy supply system to improve energy performance and meet power requirements. This system involved the installation of a broad antenna on the receiving device to gather energy. Experimental outcomes demonstrated that this system enhanced the energy storage and supply rate, specifically in dense areas, compared to device-to-device communication. Furthermore, the purpose of products involved in construction is evolving significantly. Sustainability is no longer an afterthought but a key consideration alongside core functionality. Piezoelectric flooring tiles have emerged as one of the most promising options for energy generation, particularly in heavily frequented public buildings [75]. Piezoelectric materials transform mechanical force into electrical energy, and typically consist of non-conductive substances like titanium lead zirconate (PZT) positioned between two metal plates and affixed to a base [71]. Several studies have explored the utilization of piezoelectric energy harvesting in public spaces and smart city contexts. Al Ahmad and Allataifeh [76] discussed the latest developments in piezoelectric energy harvesting concepts tailored for smart city

implementations. Elahi et al. [77] explored the mechanisms of piezoelectric-based energy harvesters (PEHs), and pointed out that PEHs help decrease reliance on batteries, leading to the optimization of structural weight. Earlier research incorporated piezoelectric tiles into various projects in Egypt, Iran, Japan, Portugal, and the Netherlands [75,78–80]. Mondal et al. [81] introduced a system design incorporating paved walkways within urban environments, aligning with the anticipation that future smart cities will play a substantial role in generating their own energy needs. The authors suggested installing PV modules on elevated sheltered structures along these walkways. These structures serve not only as shelter from adverse weather conditions for pedestrians, but also as generators of electricity. Additionally, they incorporate rainwater collection and an automated water management system for module cleaning. Lewandowska et al. [82] examined and evaluated the extent to which renewable energy infrastructure is being integrated or advanced within the urban landscape of Polish cities as a core element of the smart city paradigm. Their analysis also indicated that renewable energy installations constitute a significant component in the development of Polish cities, particularly those striving to achieve ‘smart city’ status. Additionally, the study highlighted that solar energy-based facilities largely dominate the renewable energy landscape.

Energy storage infrastructure refers to systems and technologies that store surplus energy produced in times of low demand or high renewable energy production for future usage [83]. In a smart energy system, various energy storage technologies are deployed, including batteries (such as lithium-ion batteries), thermal energy storage systems, flywheels, compressed air energy storage (CAES), and pumped hydro storage. Different forms of energy carriers have also been examined, such as methanol [84], (waste) water [85], ammonia [86,87], formic acid [88], silicon [89], and aluminum [90]. Møller et al. [91] mentioned that several methods exist for storing energy, with increasing potential for large-scale capacity: mechanical, thermal, electrochemical, and then chemical. Electrochemical and electrical storage solutions are effective for mid-range discharge times, spanning from minutes to hours, and can scale up to megawatt sizes. Mechanical storage options can achieve gigawatt-scale capacities, although their viability largely hinges on geographical considerations like the availability of mountainous lakes or underground salt caverns. Chemical energy storage, exemplified by hydrogen, boosts the most tremendous potential for large-scale energy storage. The authors also emphasized the role of hydrogen carriers in future sustainable energy systems. Modu et al. [92] highlighted the drawbacks of batteries compared to hydrogen-based storage, citing factors such as high expense, shorter lifespan, and significant size, and emphasized that hydrogen-based storage systems are a potential solution in the smart energy system landscape. The paper also offered insights into optimization methods and energy management systems, as well as a foundational framework for the integration of hydrogen renewable energy systems (HRES) with hydrogen storage. Folgado et al. [93] introduced a cutting-edge data acquisition and monitoring solution designed specifically for polymer electrolyte membrane (PEM) hydrogen generators. This system, based on an Industrial Internet of Things (IIoT) architecture, integrates industrial setup with sensors and IoT software, representing a novel approach in the field. Experimental data from a PEM electrolyzer (PEMEL) operating under real-world conditions were presented in order to demonstrate the feasibility and effectiveness of the system. The authors also discussed the crucial role of reducing reliance on conventional fuels and cutting carbon emissions. In essence, hydrogen stands out as an essential energy carrier within the realm of renewable energy and intelligent energy systems [91–95]. The concept of a hydrogen economy has been circulating for several years, with a growing focus on green hydrogen production by both businesses and governments. Integrating storage solutions into generation systems can further enhance optimization by allowing surplus energy from variable sources to be stored and utilized when demand peaks, in turn smoothing out supply fluctuations and enhancing system reliability. Accordingly, energy storage serves as a critical component in ensuring the operational stability and efficiency of smart energy systems, facilitating progress towards the goal of achieving RE100 [96]. Ultimately,

incorporating all of these elements, this holistic approach ensures that energy generation systems operate not in isolation, but in harmony with other energy sources, paving the way for a more sustainable and efficient energy future.

3. Adaptive Intelligence

The smart energy management system lies at the core of a smart energy system, serving as its central control hub. Originally, energy management systems were introduced and termed ‘control centers’ in the 1960s, and later evolved into energy control centers (ECC) by the 1970s, eventually transforming into what is now recognized as smart energy management systems [97]. A smart energy system orchestrates the efficient coordination and management of energy generation, distribution, storage, and consumption. As humankind strives for a more interconnected and eco-friendly energy horizon, the integration of ‘adaptive intelligence’ is essential for harnessing all capabilities of smart energy systems. Adaptive intelligence refers to the ability of a system to learn from and adapt to new situations, environments, or tasks. It involves the capacity to analyze and understand changing circumstances, make decisions based on that understanding, and adjust behaviors or strategies accordingly. By continuously analyzing energy generation, transmission, storage, and consumption patterns in sensors, smart meters, and IoT devices and optimizing the processes in real-time, adaptive intelligence helps maximize energy efficiency and minimize environmental impact, operational costs, and energy loss. Furthermore, it enables consumers to actively engage in energy management decisions, driving engagement and sustainability across the energy ecosystem.

Smart energy management systems leverage data analytics, automation, and control algorithms to optimize energy use, lower expenses, enhance grid stability, and support the integration of renewable energy sources. Smart energy systems utilize smart grids to merge the flow of information and energy, enabling simultaneous data collection and energy transmission by employing smart meters, sensors, automation devices, and communication networks, as well as software and analytics [98]. The first function of smart energy systems is to gather data and provide insights into energy consumption patterns, generation profiles, grid conditions, and equipment performance when it comes to functionality. Then, they use advanced analytics and optimization algorithms to analyze data, forecast energy demand, and optimize energy generation, distribution, and storage operations. Consequently, the systems automate control processes, such as load balancing, demand response, energy storage management, and distributed generation dispatch, to ensure efficient and reliable energy supply while minimizing costs and environmental impacts.

The complexity of smart energy management systems continues to grow steadily, prompting a surge in research interest recently. The literature has explored different smart energy management strategies, such as smart homes, buildings, and cities [99–102]. Additionally, the increasing popularity of big data and the Internet of Things (IoT) has proven highly beneficial for the optimization of network management processes. With the widespread adoption of emerging information technologies, vast quantities of data on energy generation and usage are being collected and processed, driving the energy sector toward digitalization.

Currently, the body of literature on big data analytics on smart energy systems primarily focuses on four key management areas: microgrids and renewables [103–105], generator-side [106–108], demand-side [109–111], as well as asset and collaborative operations [112–114]. In detail, microgrid and renewable energy management include renewable energy forecasting, hybrid system power generation, investment planning, and microgrid optimal load distribution. Economic load dispatch and power generation planning belong to the power generation side of management. Dynamic pricing, user behavior analysis, non-technical loss detection, load classification, user profiling, and load forecasting are parts of demand-side management. Asset management and collaborative operations involve system reliability improvement, fault diagnosis, operational control, and asset management. As highlighted by Zhou et al. [115], the introduction of big data is revolutionizing the en-

ergy industry landscape, enabling more intelligent energy control systems, and addressing a range of challenges such as operational inefficiency, cost escalation, and system instability. A seven-step big data-powered energy management workflow model was also proposed in [115]. System utilities draw data from four primary data sources: advanced metering infrastructure data, distribution automation data, asset management data, and third-party data [116]. Additionally, Zhou et al. [115] suggested that accurate weather forecasts are essential for smart energy management systems to make informed decisions, aiding in forecasting and system fault identification functions. The authors also pointed out that geographical information system (GIS) technology allows us to leverage rich geographical data to optimize the placement and management of electrical networks. Marinakis et al. [117] introduced a comprehensive framework for a big data cross-domain platform designed to facilitate the establishment, development, management, and utilization of intelligent energy services. In line with this framework, a web-based decision support system (DSS) was created to assist municipal authorities and energy managers in supervising the energy efficiency of their building infrastructures.

Real-time energy optimization is possible thanks to big data algorithms and models analyzing data from IoT facilities, leading to more efficient energy production, distribution, and consumption. The integration of big data and IoT technologies enables insights-driven decision-making, enhances system intelligence, and promotes long-term sustainability through efficient energy use. Saleem et al. [118] emphasized the integral role of the IoT in smart energy management systems, as it not only facilitates live data monitoring, but also enables bidirectional control of connected devices, enhancing energy management efficiency for all system stakeholders. Jia et al. [119] initially proposed a smart energy system configuration for IoT comprising three layers, which was subsequently expanded upon by Abir et al. [120]. This configuration consists of layers for data collection, data communication, and data processing:

- Data collection layer: This layer's tasks are to detect and gather data from physical devices using sensors, actuators, and wireless sensor networks (WSN). The data obtained from the sensors is later displayed on interfaces, converted into movement by actuators, or sent over the networks for subsequent analysis.
- Data communication layer: This layer is the heart of the configuration, as it includes several connectivity facilities [120]. The local area network (LAN) and wide area network (WAN) are the main parts of the layer. The LAN handles the connection between the devices of the data collection layer and the local gateway devices (i.e., end-user devices), utilizing Bluetooth, Wi-Fi, near-field communication (NFC), etc. Data transmission from LAN to the data processing layer is the task of WAN. WAN utilizes different technologies, such as narrowband Internet of Things (NB-IoT)/long-term evolution (LTE), Sigfox, and LoRa/LoRaWAN for data transmission.
- Data processing layer: This layer acts as the brain of the entire architecture. It functions as a central hub, processing, managing, and storing data, as well as providing in-depth analysis. Consequently, insights are presented to both service providers and end users in a user-friendly format. Different computing services (e.g., cloud computing, fog computing, edge computing) are employed in this layer. Cloud computing provides centralized computing resources over the internet. Fog and edge computing bring computing capabilities closer to data sources, offering advantages such as reduced latency, improved reliability, and enhanced privacy and security. Advanced techniques like machine learning and computer vision can also be employed here to unlock deeper insights from the data.

Research by Mazhar et al. [121] explored the motivations behind IoT device installation in smart energy systems, as well as contributing to the innovation of smart grids by integrating IoT and AI. The authors mentioned that the remote configuration of smart grid monitoring systems, coupled with sensors playing a vital role in overall system operation and real-time monitoring, enables network-connected devices to operate with lower energy consumption while enabling remote monitoring, thereby enhancing the security and

comfort of building occupants. Qays et al. [122] reviewed and examined the architectural design, communication technology, cutting-edge applications, and protocols of current IoT-assisted smart grid systems. The home area network (HAN) and the neighborhood area network (NAN) assist in energy management [122–124]. The HAN assists in the management of consumed energy by connecting with various household smart appliances. The NAN includes smart meters connecting with multiple HANs and is responsible for assembling the information from the installed HANs and transferring the data to the WAN. The WAN facilitates communication between power generation plants and the transmission grid. The authors also listed HTTP, CoAP, AMQP, MQTT, XMPP, CORBA, ZeroMQ, DDS, OPC UA, and DPWS as IoT protocols applied in smart grid applications, along with their advantages and disadvantages, pointing out that HTTP is the most popular protocol [122].

Subsequently, the smart grid architecture model (SGAM), a recent development, was established to provide a structured framework for designing, developing, and validating new technologies in the increasingly complex world of modern and sustainable power systems [125]. Initially conceived under the European Commission's (EC) M/490 mandate, the SGAM aimed to involve European standardization bodies, including the European Telecommunications Standards Institute (ETSI), the European Committee for Electrotechnical Standardization (CENELEC), and Comité Européen de Normalisation (CEN) [126]. Its initial focus was to evaluate existing smart grid standards and identify gaps in current practices and standardization. The SGAM functions as a reference designation system [127], consisting of three main axes for the dimensions: interoperability (interoperability layer), automation pyramid (zones), and value creation chain (domains) [128].

The interoperability layer acts as a bridge between the physical world and data exchange. It consists of five key layers, each with a specific function:

- **Business:** This layer focuses on the business side of information exchange within smart grids. It considers regulatory frameworks and economic structures that govern data flows.
- **Function:** The focus of this layer is on the various services offered by the smart grid and how they interact with each other architecturally.
- **Information:** This layer delves into the details of the information being exchanged. It defines the specific data objects and the standardized data models used to ensure clear communication.
- **Communication:** This layer specifies the protocols and mechanisms that enable components within the smart grid to exchange information seamlessly.
- **Component:** This layer represents the physical makeup of the smart grid. It details the physical distribution of all the elements involved.

Zones represent distinct hierarchical levels within ICT control systems, managing the flow of energy across different stages:

- **Market:** This zone deals with business activities related to energy trading across the entire energy conversion chain.
- **Enterprise:** This zone encompasses the commercial and organizational processes of various entities such as utilities, service providers, and traders.
- **Operation:** This zone focuses on real-time control of power systems within specific domains and includes systems for generation and transmission, as well as management systems for microgrids, virtual power plants (aggregating distributed energy resources), and electric vehicle charging fleets.
- **Station:** This zone acts as an aggregation point for data and functionalities at the field level and handles tasks like substation automation, local supervisory control and data acquisition (SCADA), plant supervision, and data concentration.
- **Field:** This zone encompasses equipment responsible for protecting, controlling, and monitoring the physical power system and includes devices that collect and utilize process data.

- **Process:** This zone represents the core physical infrastructure for energy conversion and includes the physical equipment involved (generators, transformers, lines, etc.) as well as sensors and actuators directly connected to the energy transformation process.
- **Domains in SGAM** represent the different stages of the energy conversion chain:
- **Bulk generation:** This domain focuses on large-scale electricity production from various sources. Energy generators typically connect to the transmission system.
- **Transmission:** This domain encompasses the high-voltage infrastructure responsible for transporting electricity over long distances.
- **Distribution:** This domain deals with the network that delivers electricity directly to consumers.
- **Distributed energy resources (DER):** This domain includes small-scale power generation technologies connected directly to the local distribution grid, and might be under the direct control of the distribution system operator (DSO).
- **Customer premises:** This domain encompasses the locations where electricity is used and potentially produced.

As a natural extension of IoT, the Internet of Energy (IoE), also known as energy internet (EI), expands the interconnected landscape to encompass not only devices but also the intricate networks and ecosystems they inhabit, fostering unprecedented levels of connectivity and intelligence. The term ‘IoE’ was formally introduced by Jeremy Rifkin [129] in his book ‘The Third Industrial Revolution.’ The author explored and discussed the effects of science and technology on the economy, including the energy industry. IoE is categorized as a branch of the IoT [130]. The most basic definition of the IoE is that it merges the characteristics and functions of both the smart grid and the IoT [131]. Hussain et al. [132] stated that the IoE, by utilizing ICTs, the Internet, and web technologies, enables the multi-way flow of information, communication, and energy. Kafle et al. [133] consider the IoE a revolutionary transformation in grid systems, transitioning away from centralized energy generation with unidirectional energy flow towards more efficient, reliable, and sustainable energy networks. The IoE aims to establish a resilient framework for energy exchange among users. Realizing this ambition necessitates extensive implementation of intelligent monitoring and control mechanisms, leveraging the Internet, to oversee distributed and intermittent energy production and storage effectively. The IoE system comprises three primary parts that are interconnected through ICTs: the energy, information, and network subsystems [134].

Additionally, Ahmad and Zhang [135] emphasized the potential of IoT in energy-related businesses. Firms can benefit significantly by embracing smart energy systems and advanced IoT network control solutions. These advancements offer increased convenience, efficiency, and profitability by allowing businesses to regain control and optimize their operations. Energy firms stand to gain as well, with IoT enabling them to improve grid quality, integrate renewable energy sources, and promote energy-saving behaviors. Ultimately, the deployment of IoT in the power industry offers a promising solution to reduce energy consumption and load, paving the way to seamlessly connected and efficient energy systems for all.

Furthermore, the true power of IoT in smart energy systems emerges when combined with artificial intelligence (AI)/computational intelligence (CI), unlocking a new level of efficiency and sustainability. Although IoT-enabled smart grids produce abundant data, efficiently processing and accurately selecting relevant information from this vast and complex data pool presents a significant challenge [115,136,137]. Machine learning (ML) and deep reinforcement learning (DRL) are considered the most effective approaches for analyzing this extensive data [138–142]. The term ‘machine learning’ was first defined by Arthur Samuel in 1959 as the ability for computers to learn independently without explicit programming [143]. Later, a more detailed and engineering-related definition was proposed by Tom Mitchell, which focused on how a computer program’s performance (P) on a specific task (T) improves with experience (E) [144]. Furthermore, a central area of ML is sequential decision-making, where the goal is to use experience to choose the

best series of actions in an uncertain circumstance [145]. Reinforcement learning (RL) provides a framework that allows machines to make better decisions over time. The term ‘reinforcement learning’, which drew inspiration from the principles of behavioral psychology [146], was introduced by Minsky [147]. RL is a technique for enhancing performance through a process of trial and error, resulting in empowering autonomous systems to learn independently, reducing their reliance on explicit instructions from ‘teachers’ (i.e., external sources) [148]. Deep learning (DL) acts as a powerful booster for RL by equipping agents with the ability to learn intricate patterns and make sophisticated decisions based on vast amounts of data. This powerful combination (known as DRL) leverages both RL and DL techniques. DL specializes in building intricate neural network models that can make precise decisions based on data [149]. Kelleher [149] pointed out that this technique is particularly effective for complex and extensive datasets. Ramchurn et al. [150] also highlighted that increasing the amount of training data can further enhance the accuracy of these techniques and strengthen their learning capabilities, consequently leading to better-automated decision-making. Provided that the system gains valuable insights into energy usage, grid performance, and consumer behavior by collecting vast amounts of data through IoT sensors, big data acts as the fuel for AI algorithms, enabling them to identify patterns, predict future trends, and optimize energy management strategies.

Apart from traditional ML, researchers have also introduced different innovative approaches. Cheng and Yu [151] suggested that in addition to RL and DL, ensemble learning, adversarial learning, hybrid learning, parallel learning, and transfer learning are the five prominent ML techniques representing notable advancements in smart energy sectors. The authors also anticipated significant potential for adversarial learning (AL) and parallel learning (PL) in the fields of smart grids and energy internet. AL comprises a generator and a discriminator, and has been recently introduced and exemplified by generative adversarial networks (GAN). The concept of a GAN was introduced by Goodfellow in 2014 [152] and is a recent advancement in easier and faster training processes. GANs offer several advantages in the context of smart energy systems. Their distinctive mechanism and flexibility provide greater freedom in model design and equip them with the ability to handle situations where calculating the probability density is difficult. Although GAN models still require further development to explore deeper integration with other models and address issues (e.g., mode collapse), it is believed that they will have a crucial impact on smart energy systems in the foreseeable future [151]. Additionally, within the theoretical framework of PL, predictive learning guides the exploration of temporal data, while ensemble learning determines spatial data exploration strategies, and prescriptive learning dictates data generation pathways [153]. Owing to the intensive integration of renewables, the adoption of a multi-energy complementary approach has become imperative to ensure energy reliability. PL and parallel reinforcement learning (PRL) (i.e., a novel framework that combines PL and RL) have emerged as a set of innovative ML frameworks that align with and address these needs. Presently, PL and PRL are being preliminarily employed in real-world energy system issues, especially for hybrid energy system management, and have yielded promising outcomes [151,154].

The increasing integration of internet technologies and communication protocols into energy infrastructures might pose fresh challenges to the security and seamless operation of power systems [155]. Smart energy systems collect significant volumes of data about load profiles, user behavior, and system performance. This might present vulnerabilities susceptible to exploitation, potentially resulting in the interception of confidential information and the compromise of critical electronic devices. This could lead to energy supply disruption, infrastructure damage, or even total energy system failure. Consequently, tackling cybersecurity concerns to uphold accessibility, integrity, and confidentiality in energy systems stands as the foremost priority in transitioning toward a new energy paradigm [155]. The surge in AI implementation within the power sector and smart grid control has led to rapid solutions incorporating AI models to detect cyber threats based on false data, preempting potential damage to energy systems [156,157]. Numerous research endeavors

have explored avenues for cyber-attack mitigation, including enhancements in cyber-attack detection and system protection [158–164].

Digital twins (DTs) offer innovative solutions for addressing operational and managerial smart energy system challenges associated with energy assets. The concept originated with Professor Michael Grieves in his product lifecycle management course at the University of Michigan. In essence, a DT is a virtual replica of a physical entity, encompassing three critical components: virtual products, physical products, and the connections linking them, achieved through the integration of software, hardware, and IoT technologies [165]. The power of DTs lies in their ability to create a comprehensive digital representation of a physical asset. This representation extends beyond mere functionality, encompassing details ranging from the microscopic atomic level to the macroscopic geometrical design [166]. This level of detail allows for a profound understanding of the asset's behavior and performance. Zheng et al. [167] identified the key attributes of DT technology as data fusion (i.e., integrating data streams from a multitude of physical objects), description and optimization (i.e., describing and optimizing physical objects), and lifespan management (i.e., existing and evolving alongside with physical objects as well as updating related knowledge). Cioara et al. [168] highlighted the ability of DTs in data analysis from diverse sources, the visualization and validation of physical assets, and the extraction of valuable insights for preventative maintenance and efficiency optimization.

As technology continues to evolve, DTs are poised to play a transformative role in the future of smart energy management [165], especially in smart city solutions. Agostinelli et al. [169], using the case of Rinascimento III in Rome (Italy), investigated the potential of digital twin-based techniques for optimizing and automating energy management systems. Utilizing a 3D data model, the authors employed integrated dynamic analysis algorithms to assess various scenarios of energy efficiency interventions and integrative renewable energy systems, aiming to optimize energy usage without compromising the climate and comfort control within the complex, as well as fulfill the low-impact building standards by enhancing self-produced energy levels. Wang et al. [170] also highlighted the pivotal role of DTs in the advancement and governance of smart cities, noting that the comprehensive applications of DTs in smart cities have yet to be systematically summarized and assessed. The authors also identified the driving forces, obstacles, and potential solutions and outcomes associated with DT implementation in the field of smart cities. Faliagka et al. [171] emphasized the game-changing impact of DTs on smart cities. By continuously learning and evolving, bolstered by the integration of the IoT, big data, and emerging technologies, digital twins offer real-time insights and predictive analysis capabilities. These capabilities aid in enhancing decision-making processes concerning various aspects, including interoperability and standards, urban planning, data security and privacy, resilience and emergency response, operational efficiency, and citizen participation.

Ultimately, adaptive intelligence is the catalyst for truly intelligent energy systems. It performs this function by automating the development of threat-detection algorithms and efficiently analyzing massive datasets.

4. Future Environmental Harmony

Looking at conventional energy systems, due to their predominant reliance on fossil fuels, they exert substantial environmental impacts. According to Bach [172], human activities related to fossil energy generation have a significant impact on the climate by changing the atmosphere composition through the emission of particles and trace gases (mainly carbon dioxide) and by contributing to atmospheric heat gain. Since the Industrial Revolution, the consumption of fossil fuels, along with CO₂ emissions, has been steadily rising. This increase has been largely due to human reliance on fossil fuels and deforestation practices, exacerbated by the limited capacity of the Earth's oceans to absorb excess CO₂ rapidly. CO₂ transmits shortwave solar radiation while trapping longwave radiation. Consequently, rising CO₂ levels warm the lower troposphere while cooling the stratosphere, leading to the greenhouse effect. According to Niehaus's estimation [173], by 2030, atmospheric CO₂

concentrations are anticipated to reach around 430–550 ppm, potentially causing the global average temperature to increase by approximately 0.8–1.1 °C, with other factors constant.

As humanity looks ahead to the future, the call for environmental harmony grows more urgent than ever, fueled by the pressing threat of climate crisis, pollution, and natural resource drain. Future environmental harmony refers to an ideal state where human activities are in balance with nature, ensuring sustainable use of resources, minimal ecological impact, and preservation of biodiversity for the well-being of our planet and all its inhabitants. The vision of smart energy systems is not only about technological advancement, but also represents a profound commitment to environmental stewardship. Integrating smart energy systems with the United Nations' Sustainable Development Goals (SDGs) presents a strategic pathway toward achieving a cleaner, more sustainable, and equitable world. From ensuring access to 'affordable and clean energy' (SDG 7) to fostering resilient 'industry, innovation, and infrastructure' (SDG 9), promoting 'sustainable cities and communities' (SDG 11), and tackling 'climate change' (SDG 13), smart energy systems serve as a driving force for sustainable development. Moreover, by optimizing energy usage, reducing waste, and promoting resource efficiency, smart energy initiatives contribute significantly to 'responsible consumption and production' patterns, as articulated in SDG 12. These systems, empowered by advanced technologies and renewable energy sources, hold immense potential to address key global challenges outlined in the SDGs.

Central to the environmental promise of smart energy systems is the widespread adoption of regenerative energy sources. They present a clean and abundant alternative to carbon-based energies, significantly reducing GHG emissions and air pollutants. Combining fossil fuels with renewable energy sources can yield environmental benefits, as evidenced by comparing the carbon footprints of each energy source, as shown in Table 1.

Table 1. Carbon footprint of different energy sources.

Energy Type	Carbon Footprint (gCO ₂ /kWh)
Coal	834–1026 [174], 740–910 [175]
Oil	657–866 [174]
Natural gas	398–499 [174], 410–650 [175]
Geothermal	6–79 [175], 15.1–55 [176]
Nuclear	3.7–110 [175], 9–70 [176]
Hydropower	2–48 [177]
Wave and tidal	14–119 [176]
Wind	Onshore: 6.9–14.5 [174], 7–56 [175]; offshore: 9.1–22 [174], 8–35 [175]
Solar PV	12.5–104 [174]; rooftop: 26–60 [175]; utility: 18–180 [175]
Solar thermal	8.5–11.3 [176]
Biomass	Woodchip: 25 [178], Miscanthus: 93 [178]
Ethanol	Sugar cane: 19 [179], Corn: 81–85 [180]

A study by Zhao and You [181] proposed that decarbonizing energy systems is crucial in confronting the climate crisis, and employing an optimization framework to model this transition can help design cost-effective pathways, referring to a specific case of New York State. Utilizing a bottom-up optimization approach makes decarbonization targets for electricity and space heating achievable. Meanwhile, the findings indicated that incorporating geothermal heating systems could lead to a reduction in overall system GHG emissions, particularly in scenarios with a carbon pricing policy. Specifically, with the integration of geothermal technologies, system-wide emissions could decrease by 113 million tons of CO₂-eq, accounting for 11% of the total. Moreover, Faramarzi et al. [53] investigated a multi-generation process harnessing geothermal energy through incorporating LH₂ (liquid hydrogen), fresh water, and hot water. Their findings indicated that although the high investment expense associated with hydrogen liquefaction cycles remains a challenge, employing this cycle eliminates the necessity of depending on hydrocarbon fuels for producing energy, resulting in a future-proofed energy solution with reduced environmental impact in comparison to combustion-based systems. Research by Ahmad and Alam [182] presented

a smart microgrid powered by renewable energy for a residential area in western Uttar Pradesh (India), and indicated that the system could significantly reduce air pollutants. In detail, the annual reduction in nitrogen oxide emissions was the highest at 497.73 kg, followed by sulfur dioxide (980.93 kg) and carbon dioxide (226.26 kg).

Lund et al. [183] emphasized the significance of cities in mitigating global warming. The authors explored strategies for designing energy systems aimed at increasing the utilization of renewable electricity within cities, specifically to comprehend how energy systems adapt to high renewable energy proportions and to identify achievable levels of renewable energy integration. Their findings indicated that implementing short-term storage offered the most significant marginal benefit, potentially elevating the renewable energy share of power generation to 25–35% in Helsinki, 40–60% in Delhi, and 50–70% in Shanghai. This presented a substantial opportunity for curbing CO₂ emissions from energy generation, especially for megacities like Delhi and Shanghai. Renewables displace fossil power plants in the aforementioned cases, resulting in CO₂ emission reductions commensurate with the demonstrated shares of renewables. Hence, through smart energy systems, the integration of renewables could be streamlined as part of cities' strategies for carbon reduction.

Additionally, embedding a circular economy framework within smart energy systems presents a promising avenue for addressing environmental issues. Growing populations and rising living standards have resulted in heightened material and energy footprints. This surge in consumption has not only escalated waste generation, but also correlates strongly with augmented energy usage. A circular development approach aims to keep materials and their worth circulating within the economy for extended periods. This is achieved by optimizing how waste is managed as a whole system, ensuring resources are used efficiently. Transitioning from linear to circular models of resource use, or in other words, converting waste into energy, can minimize waste generation, promote resource conservation, and reduce environmental degradation [184–186].

Within this context, Malinauskaite et al. [184] examined municipal waste management systems in a number of European nations. The authors suggested that utilizing waste as an energy source is rational, as the average heating value of municipal solid waste is around 10 MJ/kg. Waste-to-energy extends beyond the traditional association with incineration, encompassing diverse waste treatment methods that generate energy. Modern waste-to-energy facilities have the capability to generate heat and electricity with minimal environmental impact. Based on the conversion process employed, waste-to-energy technologies can be categorized into three primary groups: biochemical, physicochemical, and thermochemical. By utilizing these methods, it becomes feasible to capture useful materials from the waste stream that would otherwise be lost through complete incineration. Additionally, according to Tomić and Schneider [185], the concept of 'closing the loop' is introduced thanks to the circular economy framework. The idea of this 'game changer' is to keep materials and products in a continuous cycle. In the case of Zagreb (Croatia), authors who performed a study on the city's waste management showed that recovering energy from waste can significantly reduce the need for external energy sources. By 2030, recovering energy from 38% of waste could satisfy half the city's energy needs. This internal recycling system reduces the embodied energy of recycled materials; in other words, it increases their sustainability by 11–67%. In essence, recovering energy from waste helps 'close the loop' by turning waste into valuable resources that fuel the system itself.

Furthermore, in the pursuit of sustainability, integrating CO₂ capture into smart energy systems plays a pivotal role in lowering GHG emissions and promoting cleaner energy production. Captured carbon dioxide can be utilized in various industrial processes or stored underground using carbon capture and utilization (CCU) and carbon capture and storage (CCS) technologies. These technologies mitigate atmospheric CO₂ levels, as well as allow for carbon conversion into beneficial products, including clean energy storage solutions. Along with being a valuable carbon source for producing materials and chemicals in the chemical and agricultural sectors [187], CO₂ holds significant importance in the realm

of emerging electro-fuel technology [37]. Alternative fuels, such as biodiesel, methane, and methanol, are produced through the conversion of carbon dioxide. Specifically in the context of smart energy systems, Jarvis and Samsatli [187] suggested that the CCU technique supports the incorporation of renewables into various end-use products. Also, a study conducted by Krey et al. [188] indicated that coupling CCS and bioenergy offers the most effective approach for reducing emissions.

Carbon capture technologies have undergone significant advancements [187,189–193]. Particularly, pre-combustion, post-combustion, and oxy-combustion technologies have gained increasing interest in energy system integration [187,193]. The oxy-combustion approach refers to the process of separating air from the exhaust stream, mainly of CO₂ and water vapor. While the post-combustion approach tackles CO₂ emissions head-on by capturing it from the combustion process, the pre-combustion approach shines in terms of grid management. In detail, the pre-combustion approach offers advantages for balancing supply and demand in the energy system, as its gasification process offers flexibility and does not need to align precisely with the timing of energy generators.

5. Human-Centered Design

The term ‘energy end users’ refers to individuals, businesses, industries, or other entities that consume energy to meet their needs. Human-centered design refers to designing smart energy systems that prioritize the needs, preferences, and behaviors of users. These end users are the final recipients of energy services and might utilize different energy types, such as electricity, gas, and thermal power, in the residential, commercial, transportation, agricultural, and other sectors. Overall, energy end users play a critical role in driving energy demand and consumption patterns across the energy market [97]. Understanding the needs and behaviors of end users is essential for designing efficient energy systems, implementing energy efficiency measures, and promoting the adoption of renewable energy technologies.

Moreover, incorporating a human-centered design aspect into modeling ensures the implementation of holistic solutions that address the needs of all stakeholders. Modeling plays a crucial role in the design of smart energy systems, offering invaluable insights and optimizing efficiency to ensure the successful implementation of sustainable solutions. A smart energy system requires system modeling as the quantitative data provision source for energy system performance in decision-making processes [194]. One of the main factors in the design optimization outcomes is the set of system objectives. Single-objective optimization selects the optimal solution from available options based on a specific criterion. In practice, modeling primarily involves multi-objective fulfillment, where all objectives are simultaneously considered, resulting in different solutions with optimal combinations of these objectives. Therefore, multi-objective optimization can be viewed as a synthesis of trade-offs among several single objectives. To progress smarter and more effective development, consideration of involvement demands (i.e., objectives) is a must in the application of smart energy systems [45].

One of the problems with traditional energy systems is that long-distance remote areas encounter numerous disadvantages due to their geographical isolation and the limitations of conventional energy infrastructure. Reliability issues are prevalent, with remote areas experiencing more frequent partial or complete power outages and disruptions due to the vulnerability of transmission systems to weather-related damage or technical faults [195]. Furthermore, bringing power to remote areas is often challenging and time-consuming, leading to delays in accessing reliable electricity services. Environmental concerns arise as well, as the construction of transmission lines through environmentally sensitive areas can have adverse effects on local ecosystems and wildlife habitats. Additionally, some remote communities may rely on diesel generators or other fossil fuel-based energy sources, leading to higher emissions, pollution, and dependency on non-renewable resources [196]. Moreover, long geographical distances between energy generation facilities and consumption points cause energy wastage during power distribution [197].

Given this situation, the concept of ‘distributed energy generation systems’ was introduced as an alternative, along with the development of smart energy systems, to address these challenges and provide sustainable and equitable energy access to all communities. A distributed energy generation system is defined as a system that produces energy near the consumption point [198,199]. This system can operate with a single energy source or a combination of multiple energy sources. Subsequently, ‘decentralized energy systems’ further emphasized local control and decision-making in energy production and distribution. Decentralized systems promote resilience, sustainability, and innovation in the energy sector by empowering communities to manage their energy resources regionally. While distributed systems focus on dispersal, decentralized systems prioritize local autonomy, effectively intertwining to offer a comprehensive solution for a more resilient, sustainable, and democratized energy future. However, the literature lacks a single agreed-upon term for this concept. Alanne and Saari [200] mentioned that the term ‘distributed’ is prevalent, while ‘decentralized’ is more prevalent in Europe, whereas ‘dispersed’ and ‘embedded’ are less common. It is also important to note that while all decentralized systems are distributed, the reverse is not always true. Research on these energy generation systems is increasingly highlighting the benefits of hybrid configurations, which enhance energy generation performance and deliver improved environmental and economic outcomes [65,201–204].

Distant regions, such as islands, encounter distinct challenges due to their technical and economic constraints. A smooth transition to energy self-sufficiency and RE100 relies heavily on coordinated efforts across various sectors. This integrated approach (i.e., smart energy systems) has been assessed by examining remote area cases like Madeira Island [30], Gran Canaria Island (Spain) [205], the Islands of Pico and Faial (Azores) [206], and Huraa Island (Maldives) [207]. These studies highlighted the importance of incorporating wind and PV energy due to their accessibility and independence from importation. To optimize supply and demand flexibility and ensure the seamless shift toward RE100, it is advisable to employ dynamic pricing mechanisms and offer financial support for investment to foster strategic energy planning and incentivize consumer engagement. Additionally, advanced technologies might offer new functionalities to the energy system and warrant evaluation for their role in optimizing the integration of green energy, such as electro-fuel, smart charging, and vehicle-to-grid (V2G).

According to Ford et al. [208], the development of smart local energy systems (SLES) not only drives energy fairness and social justice but also supports local priorities and needs by involving local actors in energy provision. In detail, this engagement broadens the range of energy options available to consumers and makes it easier for them to take part in energy markets, thereby promoting a fairer energy distribution system. Also, SLESs are tailored to meet specific local requirements, ensuring convenient access for residents, providing community-focused benefits such as support for vulnerable individuals and opportunities for local employment, and addressing broader value-based concerns.

Focusing on meeting the needs and preferences of individuals and communities, particularly emphasizing accessibility, inclusivity, and well-being, is paramount in the successful integration of smart energy systems within smart homes, buildings, and cities. Smart homes are modern residential energy management systems equipped with appliances and gadgets that can be controlled from a distance by their owners [120,209]. Smart meters, connectivity infrastructure, energy storage systems, smart energy management systems, and other smart equipment are the components of the in-home infrastructure of smart homes [210]. Traditional energy monitoring is limited and inefficient, relying on manual meter readings by utility organizations. As concern for energy consumption grows, smart meters offer a solution [211], but their power is further amplified when integrated with smart home systems. Based on the IoT, this technology offers seamless convenience to residential customers by connecting with a network of smart devices. Residents can track their energy usage and manage these devices within their IoT-connected smart homes through user-friendly applications. This technology serves as a motivator for residential energy conservation, promotes efficient energy use by household appliances, and ultimately

leads to cost reductions in electricity bills [212]. In this context, as an essential system for the effective management of demand-side on smart grids, smart homes have become indispensable for household users [213].

Buildings are major energy consumers, driving the development of building energy management systems (BEMS) [214]. BEMS are a part of larger smart building management systems (BMS) and utilize a combination of computers, sensors, and actuators to automatically control everything from lighting, heating, ventilation, and air-conditioning (HVAC) to security [215]. Advancements in information and communication technology (ICT) have popularized automatic building control systems. Recent research has concentrated on enhancing BEMS functionality, particularly through two primary approaches: building information modeling (BIM) and incorporation with building control systems [216]. Additionally, there has been a growing emphasis on real-time energy management, which utilizes live weather data and energy consumption patterns to optimize energy usage, rather than relying solely on fixed rules or historical data [217].

Regarding building standards, Maier [31] considered different building standards (i.e., passive house standard vs. low energy house standard) and energy costs in a case study of the Reininghaus District (Austria). The author found that decentralized systems using building-specific heat pumps and low-temperature waste heat offered the most financially and environmentally friendly solution for supplying energy to the new buildings. Consequently, the building standard landscape evolved, with a new standard known as nearly zero energy building (nZEB). Initially, the concept of nZEBs was introduced in Article 2 of the 2010 European Union (EU) Directive 2010/31/EU, also known as the Energy Performance of Buildings Directive (EPBD) recast [218], as the EU set up a policy framework focused on reducing energy consumption and obtaining substantial savings from buildings. According to EPBD, an nZEB refers to a structure characterized by a very high energy performance, with a very low or nearly zero amount of energy that should predominantly rely on renewable energy sources, including those generated on-site or nearby, to a considerable degree [218]. In addition, zero energy building (ZEB), net zero energy building (NZEB), and others are also being applied to new constructions. These terms are often used interchangeably and have subtle differences in their definitions and goals. NZEBs are typically classified into four well-known models based on different modes of energy generation and usage: net-zero site energy buildings (i.e., buildings generate as much energy as they consume on-site, regardless of energy source), net-zero source energy buildings (i.e., buildings generate as much energy as they consume on-site, with an emphasis on source-based measurement of energy production), net-zero emissions buildings (i.e., buildings emitting minimally as much emission-free energy as they consume emission-producing energy), and net-zero cost energy buildings (i.e., building owners have zero utility bills) [219]. ZEBs can also be categorized based on energy demand and renewable installations, such as PV-ZEB, Wind-ZEB, PV-Solar thermal-heat pump ZEB, and Wind-Solar thermal-heat pump ZEB [220]. Research conducted by D'Agostino and Parker [221] in 12 European capitals underscored the crucial role of renewables in achieving the nZEB goal.

The EPBD also required the member states to customize the definitions of nZEBs to suit their specific contexts while stipulating that all new public and government buildings needed to meet the NZEB standard from 31 December 2018, and all other building types from 31 December 2020 [218]. A study by Attia et al. [222] revealed a difference in progress among EU member states regarding nZEBs. Northern and western members have been at the forefront in setting and implementing nZEB standards. Southern nations are actively working on defining nZEBs and creating implementation plans, focusing on addressing the summer overheating challenge. Meanwhile, eastern countries are still in the early stages of developing plans for widespread nZEB construction. Previous studies have also identified key factors influencing nZEB implementation across Europe, such as minimum energy efficiency standards, balancing heating/cooling requirements, ensuring thermal comfort, setting minimum thresholds for renewable energy usage, and maintaining

construction quality [222,223]. Overall, nZEBs represent a significant architectural and environmental design shift, aiming to reduce energy consumption and carbon emissions while maximizing efficiency.

The concept of nZEBs was later taken a step further with positive (or plus) energy buildings (PEBs), thanks to advancements in building technology. Compared to nZEBs, PEBs not only achieve net-zero energy consumption, but also generate a surfeit of clean energy. This surplus renewable energy can be fed back into the grid, reducing overall GHG emissions. As a result, PEBs are gaining significant attention and are expected to play a major role in future energy policies. The Horizon 2020 funding program supported numerous initiatives aimed at promoting positive energy [224,225]. Various definitions of PEB exist in the literature. At its core, a PEB is characterized by producing more energy on-site than it consumes annually, including energy used for lighting, HVAC, and all plugged-in devices [226]. To elaborate further, Ala-Juusela et al. [227] defined a PEB as an energy-efficient structure that generates more energy than it consumes, primarily through renewable sources, boosting a high self-consumption rate and energy flexibility over a year. Ensuring a high-quality indoor environment is paramount in PEB design, prioritizing the comfort and well-being of occupants. Moreover, it is capable of accommodating future technologies, such as electric vehicles, to optimize on-site consumption and facilitate surplus energy sharing. Hawila et al. [228] pointed out that a user-centric approach should be adopted for the successful implementation of PEBs to ensure occupant comfort and well-being indoors, while also fostering awareness about how their daily habits and routines influence the building's energy demands and overall effectiveness.

Beyond maximizing energy generation, PEBs require a strategic approach for managing and distributing the surplus resources they produce [229]. While PEBs are impressive achievements in sustainable design, there is potential for even more significant impact. PEBs are especially valuable where a complete shift to net-zero energy might not be feasible (e.g., old buildings and existing infrastructure) [228]. They contribute significantly to decarbonizing the building sector and offer a solution for congested energy grids. The flexibility of PEBs allows them to seamlessly integrate with the energy system, facilitating the exchange of various energy forms within buildings, communities, and the grid itself. Hence, instead of focusing on individual PEBs in isolation, assessing and enhancing building energy efficiency on a community scale is crucial, and the concept of positive energy districts (PEDs) is gaining traction [224,230]. PEDs comprise several interconnected buildings within a neighborhood that work together to regulate their energy usage and exchange energy with neighboring buildings and the broader energy grid [224,231]. Margrini et al. [224] also highlighted that through a smart energy network, they can share and distribute excess energy, collectively supporting the entire district's energy needs. This collaborative approach unlocks significant potential for a more sustainable and efficient energy future. Along with PED, positive/plus energy campus [232–234], positive/plus energy portfolio [230], and positive/plus energy community [235–238] are used to describe systems that share renewable energy resources. A campus, portfolio, and community are different in ownership: an institution owns a campus, a single entity owns a portfolio, and the occupants/users share the community, while a district encompasses a larger group, combining elements of campuses, portfolios, and communities within its boundaries [230].

Furthermore, the new energy market model gives rise to 'prosumers'. This concept was introduced by Alvin Toffler [239] in his book 'The Third Wave', and refers to individuals who both produce and consume goods or services. In the energy world, buildings are becoming prosumers. They can both consume and produce energy, often utilizing renewable sources for self-consumption while also sharing surplus energy with neighboring buildings via smart grid connections [224]. This leads to a dynamic interaction between users and the public network, where energy and information flow in both directions [240]. Traditionally, buildings have functioned solely as energy consumers, relying on electricity grids for their power needs. Subsequently, with the emergence of distributed energy sources, buildings are now able to generate their own clean energy, transforming them from passive

consumers into active participants (i.e., prosumers). These prosumers can not only power their own operations, but also potentially sell excess energy back to the grid [241,242]. A growing body of research has delved into the multifaceted role of prosumers in the energy sector in the quest for a more sustainable energy future. Research by Kühnbaach et al. [243] on prosumer participation in electricity trading in local markets suggested that from a systemic standpoint, incorporating a local market within the system offers more advantages than relying solely on self-consumption. Wesche and Dütschke [244] introduced a typology of eight archetypes and mapped the decision-making process for implementing prosuming infrastructure in small and medium-sized organizations, based on interviews in Germany. The study also identified motives, drivers, and barriers relevant to organizations becoming energy prosumers, contributing to a deeper understanding of implementation processes and critical success factors. Hu and Chuang [245] investigated how prosumers approach energy use. Their research focused on energy efficiency, achieving net-zero emissions, pursuing sustainability goals, and effective energy management strategies for prosumers. They also highlighted the key differences between prosumers and traditional energy consumers, emphasizing their unique relationship with energy. In their research, Wittmayer et al. [246] focused on collective prosumer ecosystems across Europe. They explored how these ecosystems contribute to renewable energy production, encourage citizen participation, generate local economic benefits, and foster collaboration within the broader prosumer landscape.

Expanding on the prosumer concept, the energy field has introduced the term ‘flexumer’. Coined by Bärwaldt in 2018 [247], flexumers boost the ability to adapt energy use, generation, and storage flexibly. Essentially, a flexumer enhances the energy functions of a prosumer by incorporating additional capabilities like energy storage and flexibility [248,249]. Flexumers, with their ability to regulate energy supply and demand (i.e., in response to energy network demands, operator and user requirements, and local climate conditions), offer valuable advantages to the distribution grid [248–250]. Figure 4 indicates the evolution of building energy roles, from consumers to prosumers, then flexumers. Jee et al. [251] pointed out key traits of flexumers based on price response, consistency, flexibility, and response speed, and developed a method to pinpoint them among regular consumers. Overall, the ‘flexumer’ concept offers a glimpse into the future of building energy management. However, for widespread adoption, further development is necessary, particularly in areas such as incorporating energy storage to maximize flexibility, which is further underscored by limited research on flexumers in the current literature.

Smart homes and buildings embody the fusion of cutting-edge technology and sustainable design, offering inhabitants unprecedented levels of comfort, convenience, and efficiency. From energy-efficient HVAC systems to intuitive automation features, smart buildings set the stage for the holistic transformation of urban living. Yet, as we peer beyond the walls of individual structures, the concept of smart cities unveils a broader vision, one where the seamless integration of smart buildings, infrastructure, and services converges to redefine the very fabric of urban life. A study by Albino et al. [252] referenced a substantial body of literature on ‘smart cities,’ where numerous definitions abound. Often, the term ‘smart’ is interchangeable with adjectives like ‘intelligent’ or ‘digital,’ resulting in a spectrum of conceptual interpretations. As highlighted by O’Grady and O’Hare [253], there is no singular framework or universal definition to encapsulate the essence of a smart city. Nonetheless, amidst this diversity, the core themes of ‘urbanity’, ‘smartness’, ‘interconnectivity’, ‘enhanced quality of life’, and ‘sustainability’ persist as central tenets across many interpretations. Several projects by the United States, the European Union, and the United Nations have been initiated recently, aiming to provide solutions for creating smart cities [252]. Within the domain of smart energy systems, Zygiaris’s [254] definition best captures the concept. In detail, smart cities offer an innovative approach to tackling the socio-economic and socio-technical challenges of sustainable development. The features of smart cities include:

- **Green:** Environmentally friendly infrastructure that lessens carbon emissions and protects the environment.
- **Smart:** The ability to analyze real-time data to generate valuable insights for city management.
- **Interconnected:** A robust broadband network that fuels the digital economy.
- **Innovative and knowledge-based:** A focus on fostering creativity and leveraging a skilled workforce to drive continuous innovation.

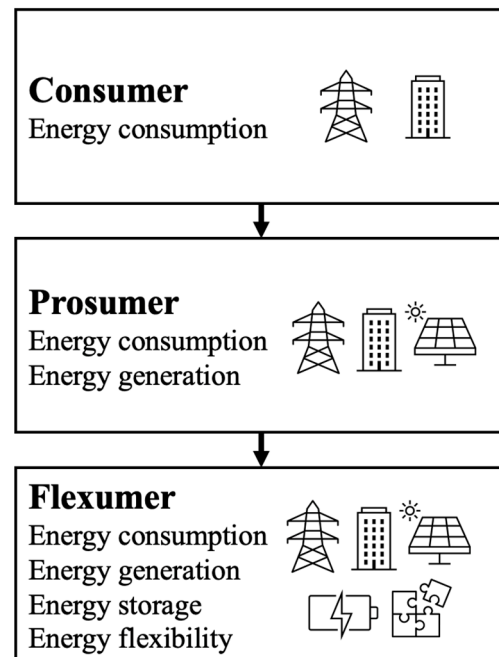


Figure 4. Evolution of building energy roles: from consumers to prosumers to flexumers.

Regarding energy system policies, buildings and electric transportation are identified as energy sinks, thus being significant sections in smart energy strategies promoting RE100 [255]. Various approaches, including maintaining current transportation demand, promoting electric vehicles, and utilizing biofuels, have been proposed for a sustainable transport sector [256,257]. Albino et al. [252] pointed out that fuel diversification (i.e., incorporating alternative energy sources) helps facilitate the transition to renewable energy in transportation. Biomass presents a viable option for replacing a considerable portion of fossil fuel consumption in transportation due to its high energy density and compatibility with existing infrastructure [49]. Nonetheless, conversion losses might occur due to overreliance on bioenergy if waste materials generated from biofuel conversion are not efficiently recycled into higher-value products [37]. Thus, encouraging the electrification of transportation becomes more compelling. It is important to highlight that when direct electricity usage is impractical, renewable electro-fuels generated by renewable electricity sources should be factored in [258,259]. The electrification of the transport sector, driven by advancements in electric vehicle (EV) technology and the transition to cleaner power grids, is becoming increasingly viable [260–262]. O'Dwyer et al. [261] highlighted that this transition necessitates establishing encouraging practices (e.g., V2G power flow) as well as a decentralized control framework that integrates renewables, storage, and fast chargers in order to optimize EV usage with the rising demand for off-grid fast-charge stations. Moreover, electrified public transport surpasses personal vehicles in both energy efficiency and sustainability [263,264], along with the growing popularity of e-bike and e-scooter rental schemes [265]. Ultimately, guaranteeing fair access to advantages and opportunities provided by smart energy systems promotes harmony among community members. This encourages active engagement in the evolution toward smart cities, thereby cultivating stronger, more resilient, and prosperous urban landscapes for everyone.

6. Conclusions

This paper conducts a literature review on the evolution of smart energy systems, exploring technological advancements and their societal implications. It presents a future design framework for these systems, emphasizing four fundamental pillars: holistic resource optimization, adaptive intelligence, environmental harmony, and human-centered design. Compared to traditional energy systems, which are heavily dependent on fossil fuels, have limited renewable integration, operate through centralized grids, and maintain separate sectors, smart energy systems offer a clear advantage. They prioritize optimizing all available resources, embracing user-friendly designs through decentralization and interconnected sectors, leveraging adaptive intelligence, and striving for long-term environmental balance. By integrating diverse energy applications and optimizing resource utilization, smart energy systems not only address present challenges but also establish the foundation for a more sustainable society.

Smart energy systems offer numerous advantages, including enhanced energy efficiency, reduced carbon emissions, and improved grid reliability. By integrating renewable energy sources, demand-side management technologies, and advanced metering infrastructure, smart energy systems enable more efficient energy production, distribution, and consumption. Additionally, these systems empower consumers with real-time energy data and control over their energy usage, promoting energy conservation and cost savings. Despite their potential, smart energy systems face obstacles that need to be addressed. The cybersecurity risk associated with smart energy systems poses a significant threat due to the potential for hacking, malware attacks, and data breaches. In addition, the integration of different energy sources poses a significant hurdle for smart energy systems. Coordinating various renewable energy sources in a seamless manner requires sophisticated management and control systems. Moreover, the high upfront costs of deploying smart energy infrastructure can create significant barriers to adoption. Furthermore, while smart energy technologies continue to advance rapidly, certain areas may still need more mature solutions, leading to compatibility issues and implementation challenges. Addressing these issues will be essential to unlock the full potential of smart energy systems and accelerate their adoption on a global scale.

Shifting to net-zero emissions will require a large-scale economic transformation, demanding complex execution. This transition will significantly impact energy demand, investment patterns, costs, and employment across various sectors, posing challenges for diverse stakeholders. This review lays the groundwork for further research by providing a descriptive analysis. However, building a robust theoretical framework remains crucial for practical applications. While this research could be beneficial in advancing sustainable energy solutions across the entire energy system, further assessments are still needed to evaluate such applications fully.

Ongoing exploration is necessary to address several key research issues in smart energy systems. A pivotal challenge lies in ensuring standardization and interoperability across the system. Smart grids rely on the integration of diverse renewable energy sources and components from various manufacturers, necessitating seamless communication for smooth operation. Additionally, integrating renewable energy sources into existing grids while upholding stability and reliability is a critical area of focus. This requires the development of efficient methods to balance supply and demand alongside advancements in energy storage technologies to mitigate intermittency. Unified standards and protocols must be developed to facilitate effortless integration. Furthermore, efficient and cost-effective energy storage solutions are crucial for wider adoption of renewables. Research efforts might be directed toward enhancing existing storage technologies and exploring alternative methods to meet this demand. Cybersecurity and data privacy represent another vital research area. Establishing robust security measures to safeguard systems from cyber threats is imperative. Researchers must balance leveraging data for optimization and protecting user privacy. Moreover, public spaces hold immense potential as sites for renewable energy generation in smart cities; however, unlocking this potential requires focused research. Em-

phasizing accessibility ensures that all members of society can benefit from these initiatives, while thoughtful design integrates energy infrastructure seamlessly into urban landscapes. Balancing technology with nature is crucial, with research needed to develop solutions that minimize environmental impact and preserve the aesthetic and ecological integrity of public spaces.

Furthermore, emerging trends are shaping the future of smart energy systems, promising significant advancements. The integration of AI and ML stands out, revolutionizing smart grids by enhancing energy optimization, predicting demand, and refining grid management through real-time analysis. Blockchain technology emerges as another trend, offering secure and transparent energy transaction management in decentralized grids, potentially fostering a more efficient and participatory energy market. Demand-side management (DSM) also sees notable development, incentivizing consumers to adjust energy usage during peak hours and alleviating grid strain. Leveraging IoT and its subcategories, such as IoE and DT, is pivotal for real-time data collection on energy consumption and grid conditions, driving efficiency improvements and deeper insights. Moreover, adherence to building standards like nZEB and PEB, as well as accommodating prosumers and flexumers, are essential, demanding advanced technologies and intelligent energy management to achieve the sustainability objectives of smart energy systems.

Ultimately, to advance smart energy systems, policymakers should implement supportive policies that incentivize investment in infrastructure, research, and development. This encompasses financial incentives such as tax credits, regulatory frameworks to spur innovation, and public–private partnerships to facilitate technology deployment. Moreover, prioritizing consumer education and awareness campaigns promotes participation in energy conservation. Planning and implementing smart energy systems involves collaboration among diverse stakeholders, necessitating reliable methods to design and assess energy systems. Additionally, inclusive design of smart energy interfaces, with features for diverse abilities and clear visuals, is the key to unlocking both economic and social benefits. Making smart energy technologies affordable and offering flexible payment options promotes financial inclusivity while acknowledging cultural diversity, and involving communities in the design process fosters solutions tailored to local needs and preferences.

Author Contributions: Conceptualization, J.-L.H. and N.H.B.B.; methodology, J.-L.H. and N.H.B.B.; software, J.-L.H. and N.H.B.B.; validation, J.-L.H. and N.H.B.B.; formal analysis, J.-L.H. and N.H.B.B.; investigation, J.-L.H. and N.H.B.B.; resources, J.-L.H.; data curation, N.H.B.B.; writing—original draft preparation, J.-L.H. and N.H.B.B.; writing—review and editing, J.-L.H. and N.H.B.B.; visualization, N.H.B.B.; supervision, J.-L.H.; project administration, J.-L.H.; funding acquisition, J.-L.H. All authors have read and agreed to the published version of the manuscript.

Funding: The first author gratefully acknowledges partial financial support from Taiwan’s National Science and Technology Council (112-2410-H-A49-072).

Acknowledgments: The authors would like to thank the two anonymous reviewers and the academic editor for their insightful comments and valuable suggestions on improving this study.

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

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