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Review

A Review of Smart Energy Management in Residential Buildings for Smart Cities

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Abstract: This survey critically examines the integration of energy management systems within smart residential buildings, serving as key nodes in the smart city network. It systematically maps out the intricate relationships between smart grid technologies, energy storage capabilities, infrastructure development, and their confluence in residential settings. From the evolution of power generation methods, incorporating both traditional and renewable sources, to the cutting-edge progress in energy-efficient transport systems, we assess their cumulative impact on the smart urban environment. While our approach is rooted in theoretical exploration rather than mathematical modeling, we provide a comprehensive review of the prevailing frameworks and methodologies that drive energy management in smart urban ecosystems. We also discuss the implications of these systems on urban sustainability and the critical importance of integrating various energy domains to facilitate effective energy governance. By bringing together a diverse array of scholarly insights, our paper aspires to enhance the understanding of energy interdependencies in smart cities and to catalyze the development of innovative, sustainable policies and practices that will define the future of urban energy management. Through this expanded perspective, we underscore the necessity of cross-disciplinary research and the adoption of holistic strategies to optimize energy usage, reduce carbon footprints, and promote resilient urban living in the era of smart cities.

Keywords: smart cities; energy management; smart grid; renewable management; non-renewable management

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1. Introduction

This paper explores the notion of the smart city, which is a modern idea that has gained a lot of attention and is being used in real life to address the problems caused by increasing urbanization and population expansion. This study offers a thorough analysis of important aspects of the smart city, such as waste management, transportation, and energy provision, in addition to theoretical insights. The primary goal is to advance sustainable energy practices by optimizing resources and maximizing efficiency. In order to make the move from fossil fuels to cleaner, renewable energy sources, sustainable energy development involves a variety of technologies that advance infrastructure, smart grid systems, energy storage, power generation, and power generating [1]. By reducing our reliance on central power plants, distributed generation (DG)—such as rooftop solar panels—improves grid stability [2]. This has significant financial advantages. By utilizing ICT, smart city development raises the standard of living for citizens while reducing waste and increasing energy efficiency. We can come closer to a future with more sustainable energy by incorporating these innovations. A key element of modern smart cities are smart residential buildings, which are distinguished by a combination of cutting-edge technology, creative design, and environmentally friendly methods. In terms of functionality and potential, these buildings are a sharp contrast to standard residential buildings.

Smart residential buildings, in contrast to traditional residences, are furnished with an array of intelligent systems that facilitate energy-efficient functioning, heightened comfort, and a higher standard of living for occupants. They use state-of-the-art technologies, like home automation, advanced data analytics, and Internet of Things (IoT) sensors, to optimize energy use, lessen their influence on the environment, and boost the building's overall efficiency.

With a strong emphasis on user interaction, smart residential buildings enable residents to remotely monitor and manage a range of home features, such as security, heating, cooling, and lighting. In order to encourage sustainability and resilience, these structures frequently include energy storage systems in addition to renewable energy sources like solar panels. Furthermore, because they interface with other urban components including power generation, energy storage, infrastructure development, and smart grid systems, smart residential buildings are an essential part of the larger smart city framework. As a result of this interaction, the urban environment becomes more dynamic and better energy management and urban living standards are achieved [2–6].

The energy requirements of metropolitan regions are complex and significant. Consequently, modern cities must improve their current infrastructures and implement innovative solutions in a coordinated fashion, utilizing an ideal approach that capitalizes on the inherent synergy of these many energy alternatives. The relevance of implementing a comprehensive strategy for energy management is underscored by various challenges, including the irregular nature of renewable resources, increasing energy demands, and the need for energy-efficient transportation systems. This highlights the importance of moving away from the traditional fragmented approach [3]. Simulation frameworks have been developed with the purpose of assisting stakeholders in understanding the complexities of urban dynamics and evaluating the impacts of different energy policy choices. However, it is common for these efforts to often analyze energy domains separately, disregarding the holistic viewpoint and thereby leading to less-than-optimal results. The implementation of a comprehensive smart city model that incorporates all energy-related activities, while also ensuring a manageable scale and complexity, offers significant benefits in meeting the increasing energy demands of present and future urban environments.

This study presents an extensive survey that, within the larger context of smart cities, uniquely synthesizes the corpus of available information on smart residential buildings. Our study is unique because of its comprehensive methodology. First, in order to present a comprehensive understanding of the topic, we have carried out a thorough review of the literature, combining insights from multiple sources. Secondly, we have utilized a methodical approach that includes an analysis of the main areas of intervention: energy storage, infrastructure development, smart city energy modeling and integration into residential and commercial buildings, progress in the energy usage of transportation systems, and energy modeling methods for smart cities, all of which are critical to the development of smart cities. In doing so, we uncover important connections and interdependencies that have never been thoroughly investigated before. Finally, we emphasize the most important conclusions and drawbacks for field researchers and practitioners. Our survey offers useful insights for researchers and professionals working in the fields of smart cities and smart residential buildings.

Our research highlights the complex interrelationships that exist between energy storage, smart grid systems, infrastructure development, and power generation in the context of smart residential buildings. Improving sustainability, maximizing energy management, and raising the general quality of life in urban environments all depend on these relationships. Stakeholders may adopt policies, make well-informed decisions, and aid in the development of more sustainable and intelligent cities by having a better grasp of these dynamics. (See Figure 1): generation, storage, infrastructure, buildings, and transportation (mobility); these domains demonstrate interconnectedness while making distinct contributions to the energy framework. Generation is responsible for supplying energy, storage ensures its availability, infrastructure facilitates energy distribution and user interactions, and both buildings and transportation serve as crucial end-users of energy, utilizing it for their operations. The functioning of energy systems relies on three fundamental components: intellect (control/management), communication, and hardware (physical components and devices).

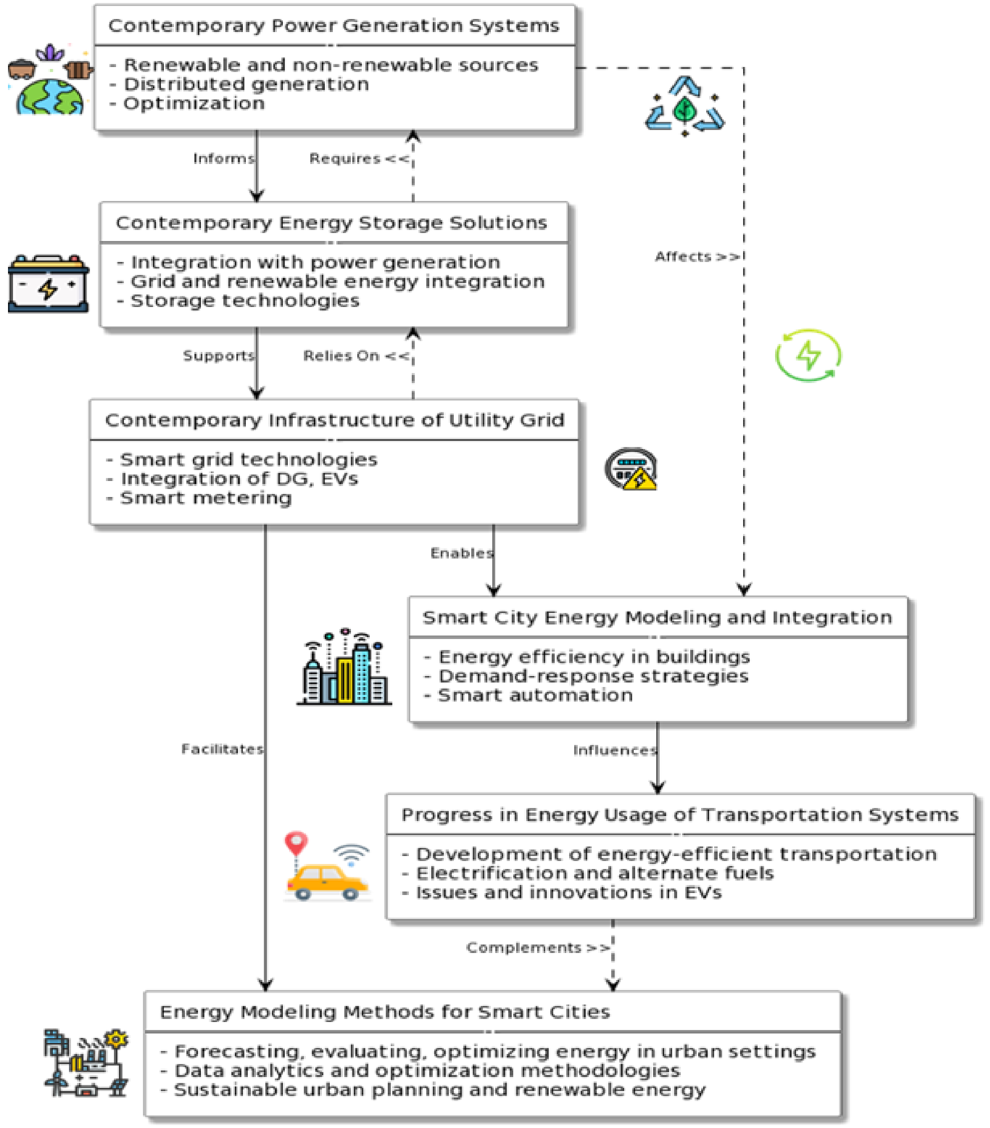


Figure 1. Hierarchical structure of smart city energy management Systems.

The core contribution of this study regarding the advance of knowledge in smart city-distributed energy generation revolves around the following:

1. Comprehensive Hybrid DG Evaluation: our study thoroughly evaluates hybrid DG systems, covering their sizing, integration, and control configurations.
2. Diverse Energy Source Modeling: unlike prior work focusing on single sources, we model various DG technologies for their economic and technical feasibility.
3. Simulation Tool Comparison: we compare HOMER and DERCAM outcomes, guiding tool selection for microgrid planning in our study.
4. Urban Context and Transportation Focus: acknowledging model limitations, we emphasize addressing urban and transportation complexities in DG research.

5. Critical Economic Metrics Assessment: we critically analyze economic metrics' diversity, cautioning against hasty comparisons due to varying factors.

These points entail providing solutions that enable the effective modeling and control of energy systems, while also analyzing existing initiatives and software tools. These strategies incorporate essential components and fundamental data sources necessary for their mathematical depiction. This paper is organized into two primary sections. The initial portion of the paper (Sections 2–7) provides a thorough analysis of the research carried out in selected energy intervention fields, with a specific focus on their relevance to smart cities. Section 2 of the study focuses on the advancements in energy generation specifically within smart urban environments. In the subsequent section, an assessment of several storage systems and their practical implementations is provided. Section 4 delves into an examination of the technological environment and future possibilities for infrastructure, while Section 5 sheds light on energy-related technologies and systems that have been deployed inside the smart grid. Section 6 explores the progress made in relation to the energy usage of transportation systems.

The subsequent portion, identified as Section 7, comprises a thorough assessment of existing energy modeling methods specifically designed for smart cities. Additionally, it presents a comprehensive methodology for the planning and operation of energy systems. Ultimately, the study reaches its culmination in Section 8, wherein concluding remarks and recommendations are expounded upon.

Foundations of the Smart City Energy Ecosystem

Several power generation sources, such as distributed generation, non-renewable and renewable sources, and optimization techniques, are represented in this section. This varied mix of generations may provide energy for smart parking and smart transit. For example, in smart mobility, conventional grid power as well as renewable energy sources could power EV charging stations. The modern electricity grid connects the entities in this area of the smart city. Smart technologies ensure a more sustainable and efficient power supply by optimizing the distribution and consumption of electricity.

Solutions for energy storage are essential for storing the extra energy produced during peak hours. Energy storage systems could be used by smart parking and transportation corporations to store electricity, particularly when using intermittent renewable energy sources. This section covers smart cities' integration with renewable energy sources, the grid, and power generation. A comprehensive network for energy distribution and storage can be formed by connecting energy storage solutions to distributed generation systems, renewable energy sources, and the power grid.

Distributed generation, smart metering, electrical cars, and smart grid technologies are all included in this section. This grid's essential elements, smart parking and mobility, get their energy and information from utility infrastructure. The smooth integration of multiple components is guaranteed by smart grid technologies. For instance, dispersed generation is connected into the grid for optimal energy distribution, and smart meters offer real-time data on energy consumption.

This section focuses on demand response tactics, intelligent automation, and building energy efficiency. The energy-saving measures put in place in buildings may help smart parking systems, while demand response techniques might help smart mobility use energy more efficiently. The smart city's overall energy efficiency is enhanced by the combination of these components. A coherent implementation of energy modeling strategies across various sectors is ensured through data exchange and communication mechanisms.

The energy-saving innovations in transportation systems, such as electric cars and other environmentally friendly forms of transportation, are discussed in this section. Smart transportation entities based on electric power show how transportation has become more energy-efficient over time. The successful operation of sustainable transportation networks depends on a combination of smart grid technology and renewable energy sources. The network is interconnected and includes infrastructure for vehicle-to-grid (V2G) communication and charging.

The techniques and resources utilized for modeling and optimizing energy use in smart cities are properly covered in this last part. It helps with the general comprehension and planning of energy use in the setting of the smart city that is shown. The strategies and models discussed in this section can be linked to real-time data from energy storage systems, smart grid technologies, and other infrastructure elements of smart cities. Their energy models are guaranteed to be dynamic and adaptable to changing circumstances because of this connectedness.

To summarize, Figure 1 provides an overview of the current state of the smart city energy ecosystem by showing how energy storage, power generation, utility grid infrastructure, smart city modeling, and transportation systems are all interconnected. The broader framework serves as the source of electricity and connectivity for many entities, including smart parking and smart transportation, which enhance the sustainability and efficiency of the smart city as a whole.

2. Contemporary Power Generation Systems

The core of the subject is "Contemporary Power Generation Systems", which encompass both renewable and non-renewable sources. These systems play a crucial role in distributed generation and the efficient utilization of energy resources. The foundation of "Contemporary Energy Storage Solutions" is predicated on its strong integration with power generation, hence providing stability by leveraging storage technologies. The aforementioned storage solutions are dependent on and interconnected with the "Contemporary Infrastructure of Utility Grid", which is distinguished by its utilization of sophisticated smart grid technologies and the incorporation of distributed generation (DG) and electric vehicles (EVs). At their peak, these interrelated systems provide "Smart City Energy Modeling and Integration", which prioritizes the improvement of energy efficiency in buildings, the implementation of demand response methods, and the integration of intelligent automation for the purpose of optimizing energy use.

Moreover, Figure 1 illustrates an energy management target that functions as a foundational input for urban policy. This approach utilizes key performance indicators (KPIs) to offer vital data that is needed for making well-informed decisions. By employing machine learning and optimization techniques, the KPI values are converted into actionable insights, hence promoting enhanced energy management within the smart city system. This comprehensive approach underscores the complex interplay between policy development, data-driven analysis, and dynamic optimization methods, all of which jointly contribute to the improvement of energy efficiency and sustainability in smart urban settings.

In the field of energy generation, it is essential to investigate energy management systems that maximize power generation in addition to exploring other sources such as renewable and non-renewable energy. Comprehensively reviewing and comprehending the function of energy management in these systems will greatly enhance our overarching view [4]. However, it is worth noting that alternative non-renewable sources, such as the combined heat and power (CHP) fueled by natural gas and biomass generation, have been recognized for their relatively lower environmental impact compared to conventional methods [5,6]. These sources can also be considered feasible short-term solutions for reducing emissions and meeting energy demands [6]. However, the emergence of distributed generation (DG) is becoming a central focus, as it presents potential benefits in improving efficiency and contributing to the reliability and resilience of the grid [7]. Extensive research has been conducted on the advantages and requirements associated with distributed generation [6,8]. It is important to acknowledge that the advancement of a smart city towards a comprehensive renewable energy framework holds great importance, and distributed generation (DG) can play a crucial role in achieving this goal. Therefore, although traditional power generation may continue to exist in smart cities during the immediate and intermediate stages, its examination is beyond the purview of this section.

2.1. Comprehensive Details of Contemporary Power Generation Systems with an Emphasis on Energy Management Systems

Diverse energy choices can be efficiently incorporated into the structure of a smart city. Table 1 presents a succinct summary of the key characteristics linked to the examined technologies herein.

A sustainable energy infrastructure must include renewable energy sources and energy management, which includes technology such as photovoltaic (PV) panels, wind turbines, and biomass generation. For maximum efficiency, however, their erratic nature, stemming from their reliance on external factors, necessitates their integration with sophisticated energy management systems [9–13]. Solar energy panels use weather-related fluctuations to turn sunlight into electricity. Power output is tracked and predicted by advanced energy management systems [9], which guarantee a balance of supply and demand and grid integration. Though plentiful, wind energy is unpredictable as wind patterns fluctuate. Customized energy management systems anticipate changes in the grid and modify their power output accordingly [10,11]. Material variations are a barrier for biomass energy. By employing sophisticated control systems to optimize fuel supply, integrated energy management [12,13] guarantees a consistent and effective energy output. It is considered a dependable source for heating water or other substances that transfer heat, and has uses in various fields [14]. Thermal collectors (TCs) demonstrate cost-effectiveness when implemented on a restricted scope and can also be utilized in concentrated solar-power (CSP) facilities to produce electricity on a utility scale [15]. Usually, they are utilized in tandem with thermal power generation systems. Despite the fact that the levelized cost of energy (LCOE) for this method of generation is competitive, it is not well-suited to urban contexts. In addition, photovoltaic–thermal collectors (PV/T) operate similarly to conventional solar cells, while simultaneously providing thermal energy, which aids in the heating of water or fluids. PV/T systems have enhanced efficiency; yet, the market exhibits a scarcity of commercial modules, most of which are available in restricted quantities [16]. Wind turbines (WT) are specifically engineered to capture and utilize the kinetic energy present in the flow of air, thereby converting it into either mechanical or electrical energy. Over the course of its development, this technology has reached a state of maturity and now encompasses a wide array of system sizes, thereby enabling the economically viable generation of energy at a large scale. However, the economic feasibility of the aforementioned wind turbine decreases when implemented on a smaller scale. Due to the inherent instability and unpredictability of wind patterns, it is common practice to supplement wind turbines with supplementary energy sources or storage devices when employed for smaller-scale applications. The importance of biomass has been increasingly recognized in recent years. The resource in question possesses a wide range of applications in the field of energy, as it can be utilized for heat generation through combustion or transformed into gaseous or liquid biofuels. These biofuels have the ability to generate heat or electricity at rates that are comparable to other sources, making them a viable option [1].

Nevertheless, the production of biomass crops requires a prudent approach in order to guarantee their long-term viability. It is important to highlight that recent European directives impose restrictions on the utilization of first-generation biofuels, which rely on sugars and vegetable oils derived from cultivated crops. However, the same directives promote the use of second-generation biomass derived from woody crops, agricultural leftovers, and waste materials [1]. Geothermal energy is derived from the transfer of heat that comes from the Earth's core. This form of energy is generally utilized for thermal production at low to medium temperatures, as well as co-generation at higher temperatures. The economic viability of geothermal energy generation is significantly enhanced in the presence of suitable sub-surface conditions. However, it should be noted that the occurrence of certain soil features is restricted in urban locations [17]. The notion of poly-generation, also known as multi-generation, has emerged as a means to improve the efficiency of fossil fuel consumption. This is accomplished through the utilization of diverse energy generation methods derived from a singular fuel source, frequently entailing the combustion of natural gas for the purpose of power production, while simultaneously harnessing the remaining heat for alternative applications. The aforementioned methodology not only enhances overall efficacy, but also plays a role in mitigating carbon dioxide emissions [4]. However, it is important to note that this technology does have a notable drawback in terms of its elevated costs when implemented on a restricted scale [18]. One example of a viable solution for small-scale energy generation is hydrogen fuel cells. However, it is important to note that the cost associated with the energy produced by these fuel cells is higher than that of standard generation methods.

2.2. Contemporary Techniques for Distributed Power Generation Systems

A critical research dilemma pertaining to distributed generation (DG) centers on determining the most advantageous configuration, location, type, and capacity of the generation units. The objective of this endeavor is to ensure that the system efficiently meets energy requirements while minimizing costs [3]. Biomass is a versatile, renewable energy source crucial for a cleaner and sustainable future. It finds applications in power generation, energy storage, infrastructure, and smart grid systems. Biomass's significance in meeting local energy demands in developing countries highlights its affordability and availability [19]. Biomass contributes to reducing greenhouse gas emissions, offering alternatives in terms of power generation (combustion, pyrolysis, gasification), energy storage (pellets, biofuels), infrastructure development (biofuels, biomaterials), and smart grid systems for flexible electricity supply. This evaluation of biomass encompasses various aspects, including sizing approaches and integration configurations. These configurations include DC-coupled, AC-coupled, or hybrid DC–AC-coupled setups. Furthermore, various control system configurations, including centralized, decentralized, and hybrid approaches, were comprehensively addressed in a recent study [20].

Based on the instances documented in the current body of research, it becomes apparent that a considerable number of distributed generation (DG) schemes consist of hybrid configurations that incorporate several sources of generation. As an example, one instance of the application of solar power for the purpose of generating both heat and electricity within buildings is demonstrated in [21]. While this study does investigate geothermal heat pumps (GHP), it does not provide a thorough analysis of other relevant energy sources, and the accuracy of its cost estimates is unclear. Another study [22] explores the concept of poly-generation, utilizing natural gas as a power source. The study introduces a comprehensive framework for assessing the energy efficiency and carbon dioxide (CO_2) emissions associated with this approach. Nevertheless, this research exhibits a deficiency in addressing the economic aspects of this power source and fails to incorporate a comparative analysis of competing technologies [23].

Regarding the environmental impact of natural gas and biomass generation, it is essential to clarify that the claim of a relatively lower environmental impact is made in a comparative context. The environmental impact of energy sources is a complex issue, and the statement in Section 2.2 takes into account multiple factors. While natural gas combustion releases greenhouse gases, its overall emissions, particularly of carbon dioxide (CO_2), are generally lower than other fossil fuels such as coal and oil. Methane, the primary component of natural gas, has a shorter atmospheric lifetime than CO_2, leading to less persistent warming effects. Biomass generation, discussed in the same section, involves the use of organic materials and is considered a renewable energy source, with carbon emissions theoretically reabsorbed by the next generation of plants. The claim acknowledges that natural gas and biomass are not entirely without environmental impact but suggests that, in comparison to certain alternatives, they may offer a more environmentally friendly option.

Similarly, in reference to distributed generation (DG) systems, the contemporary state of the art [24,25] combines the modeling of several DG technologies and assesses their economic and technical feasibility. The first article provides an analytical approach to determining the appropriate size of DG systems, while the second article discusses a linear programming problem related to DG systems. Both papers examine DG systems using a single-node technique, which is worth mentioning. In contrast to previous instances where DG systems were formed using different methodologies, numerous notable applications now utilize specialized software tools for this purpose. Article [26] offers a comprehensive examination of 37 specific computer applications that are well-suited for assessing the combination of renewable energy sources. Among the several tools examined, HOMER [27] stands out as particularly notable. The software, created by the National Renewable Energy Laboratory [28], has garnered significant recognition and is widely employed in academic research. In the aforementioned study, the authors make use of HOMER to showcase its effectiveness in improving the planning of DG for microgrids located in Serbia [7]. In this study, the authors determine the most effective combination of technologies in several scenarios with limitations to their CO_2 reduction. This involves the examination of combined heat and power (CHP), micro-hydro, photovoltaic (PV), and wind turbine (WT) systems. Another tool that can be compared in this field is DERCAM, developed by Berkeley Lab [29]. One of the uses of this tool involves evaluating the impact of electric vehicles (EVs) on other distributed energy resource (DER) solutions, while also considering the uncertainty associated with EV driving schedules [30]. The referenced texts provides a comprehensive overview of various applications that utilize these tools [1,16,24]. These applications encompass a wide range of practical implementations of DG systems. It is imperative to emphasize that the range of software tools that are currently available has been extensively scrutinized in the existing body of literature. This assessment has been conducted using various approaches [21,31,32]. The examined tools mostly focus on simulating power systems. While a subset of the tools does address the heat or transportation sectors, it is important to note that their application area and the technology they embrace are constrained by certain limits. It is worth mentioning that there are only three tools that possess the ability to encompass the domains of electricity, heat, and transportation [21]. The utilization of these instruments has been applied in the simulation of systems that rely solely on renewable sources, without any dependence on traditional forms of power generation. Nevertheless, it is imperative to recognize that these tools do not capture the entirety of the wide range of transportation and generation technologies and storage systems that are distinctive of urban contexts. Moreover, these tools are specifically designed to achieve specific goals, generally focused on evaluating the consequences of different marketing techniques.

Hence, the suitability of these approaches may present difficulties when dealing with alternative problem domains. As previously mentioned, these models have been developed with certain focal areas and purposes, resulting in differences in the technologies included and the level of complexity incorporated into the models. These factors can have an impact on the resulting outcomes. In order to demonstrate this point, the authors of [33] choose one-hour time intervals and conduct a simulation that covers a period of one year. This choice of time intervals and simulation duration is in line with the objective of the study, which was to determine the most effective investment and operation scheduling for distributed energy resources (DER). In contrast, study [34] conducts an examination of the most efficient functioning of household appliances within the framework of five-minute intervals, while also accounting for the uncertainties associated with electricity pricing.

In contrast to the study mentioned earlier, this technique prioritizes real-time operation rather than investment planning, resulting in a difference in the level of detail in the temporal intervals. A notable example is shown in [35], where the authors analyze a distributed generation (DG) case study using two different software tools, specifically, HOMER and RETScreen. Interestingly, significant differences in the DG production outcomes are seen, even when both tools are exposed to similar inputs. Therefore, it is crucial to carefully evaluate and select the most suitable model or tool, ensuring that the chosen software corresponds to the necessary qualities and desired outcomes for its intended application. Numerous research attempts focus on the technological aspects inherent in distributed generation (DG) to assess its practicality. An illustration of this emphasis can be observed in [36], which presents a comprehensive analysis that includes flexible AC transmission systems (FACTS) and distributed generation (DG) systems, as well as their impacts on a network. This study explores several techniques pertaining to the deployment of these systems and the coordination of control strategies. It is important to acknowledge that certain sources are frequently mentioned because they provide a detailed examination of different distributed generation systems. A table below highlights the variability in the achieved results and the contrasting methods of presentation observed in the different studies. Not all studies include statistics pertaining to the reduction of CO_2 emissions, for example. Moreover, economic data, such as payback periods or projected benefits (referred to as a return on investment (ROI)), demonstrate the significant diversity among various studies. The observed variance is notably significant, taking into consideration the year in which the study was conducted and the precise pricing factors that were considered. Therefore, it is advisable to exercise caution when comparing different systems and approaches, considering their potential limits, the valuable insights provided by economic measures and research notwithstanding. In general, optimization procedures tend to produce superior expected profits when compared to alternative methodologies. The optimal sizing of systems that depend on renewable energy sources has the potential to significantly improve their economic and technical efficiency [37]. This optimization aims to promote the widespread adoption of ecologically friendly resources. Table 1 presents a comprehensive summary of multiple studies that examine the applications and technologies associated with distributed power production systems.

Table 1. Contemporary applications and tools for distributed power generation systems.

Study	Focus	Approach	Technologies Explored	Findings	Merits	Demerits
[3]	Renewable Energy Sources	Long-term investments for energy self-sufficiency	Renewable energy sources	Emphasis on achieving sustainability and safeguarding future generations' interests	Reduces carbon footprint	Initial investment costs
[4]	Non-Renewable Sources	Short-term emission reduction	Combined heat and power (CHP), natural gas, biomass generation	Viable short-term options for emission reduction and meeting energy requirements	Provides short-term emission reduction	Finite fuel resources
[5]	Distributed Generation (DG)	Enhancing efficiency and grid resilience	Distributed generation (DG) systems	DG offers advantages in efficiency, grid dependability, and resilience	Increases grid resilience	Scalability challenges
[6]	Renewable Energy Framework	Role of DG in renewable energy transition	Distributed generation (DG) systems	DG plays a pivotal role in realizing a fully renewable energy framework for smart cities	Facilitates renewable energy transition	Coordination complexity
[1]	Hybrid DG Systems' Design	Sizing and integration configurations	Hybrid DG systems	Comprehensive assessment of design facets for hybrid DG systems	Improves system efficiency	Integration complexity
[17]	Solar Power in Buildings	Solar power for thermal and electrical generation	Photovoltaic (PV) panels, geothermal heat pumps (GHP)	Solar power used for thermal and electrical generation in buildings	Utilizes renewable energy	Weather-dependent

Table 1. *Cont.*

Study	Focus	Approach	Technologies Explored	Findings	Merits	Demerits
[18]	Poly-Generation with Natural Gas	Multi-generation from a single fuel source	Natural gas	Model for evaluating energy performance and CO_2 emissions of poly-generation	Efficient utilization of fuel	Emission concerns
[19]	Economic and Technical Viability	Range of DG technologies	DG technologies	Evaluation of economic and technical viability of multiple DG technologies	Guides technological investment	Capital and operational costs
[20]	Economic and Technical Viability	DG systems employing a singular-node approach	DG technologies	Examination of economic and technical viability of DG technologies	Assesses feasibility of technology	Complex economic modeling
[21]	Software Tools Overview	HOMER, DERCAM, and other tools	Various DG technologies	Overview of software tools suitable for evaluating renewable energy integration	Facilitates evaluation of technology	Software learning curve
[23]	DG Planning Optimization	Microgrids in Serbia	Combined heat and power (CHP), micro-hydro, photovoltaic (PV), and wind turbine (WT) systems	Optimizing DG planning for microgrids with diverse scenarios	Enhances microgrid planning	Integration challenges
[24]	Distributed Generation Modeling	HOMER and RETScreen tools	Distributed generation (DG) systems	Application of software tools in modeling DG systems	Enables accurate modeling	Data accuracy requirements
[26]	Distributed Energy Resources	One-hour time intervals, simulation for a year	Distributed energy resources (DER)	Optimal DER investment and operational scheduling	Optimizes energy resource utilization	Complex simulation setup
[38]	Technical Aspects of DG	FACTS and DG systems, network repercussions	Flexible AC transmission systems (FACTS), DG systems	Examination of technical facets of FACTS and DG systems on networks	Enhances network understanding	Technological complexity
[39]	Non-Technical Challenges	Competitive mechanisms and regulatory frameworks	Distributed generation (DG) systems	Exploration of non-technical challenges in DG implementation	Identifies regulatory challenges	

At present, most distributed generation (DG) research concentrates on particular energy sources in hybrid configurations; thorough evaluations of diverse energy sources are scarce. For example, research on the combination of solar power and natural gas [40,41] does not include detailed economic analyses or comparisons with competing technologies [27,28]. Using tools like HOMER and DERCAM, more recent research uses modeling to evaluate the technical and financial viability of various distributed generation technologies [19,20]. However, these models may not be fully capable of replicating urban energy systems or resolving transportation-related issues [21,24,25]. The results produced in [21,26,42] are impacted by the varying complexities of the models used.

In addressing the potential limitations of these models and simulations, there are difficulties because different studies have different simulation times and intervals [43]. Certain studies employ distinct temporal resolutions, such as one-hour intervals spaced one year apart or five-minute intervals [26], which correspond to particular goals, some pertaining to real-time operation, others to investment planning. Even with equal inputs, different software tools can produce very different results [44]. Choosing the appropriate models with care is essential, taking learning objectives into account. Research frequently concentrates on the technological components of DG without adhering to standard procedures for presenting findings, especially when it comes to CO_2 emissions or economic metrics [21,26].

Figure 2 illustrates the essential characteristics of different power production methods as outlined in the section dedicated to contemporary power generation systems. The array of technologies encompasses solar panels, thermal collectors, wind turbines, biomass systems, geothermal energy, and poly-generation. It is evident that various energy resources, such as Solar TC, SOLAR CSP, Solar PV/T, wind power, poly-gen, biomass, and geothermal, collectively account for approximately 60% of energy efficiency. However, solar PV alone contributes 30% to this overall energy efficiency [29]. Furthermore, Figure 2 illustrates the results of this analysis in the form of a pie chart. The majority of energy efficiency is attributed to solar-concentrated solar power (CSP), with a contribution of 145 units. This is followed by geothermal, biomass, poly-gen, wind power, and solar photovoltaic/thermal (PV/T), each accounting for 13% of the total energy efficiency.

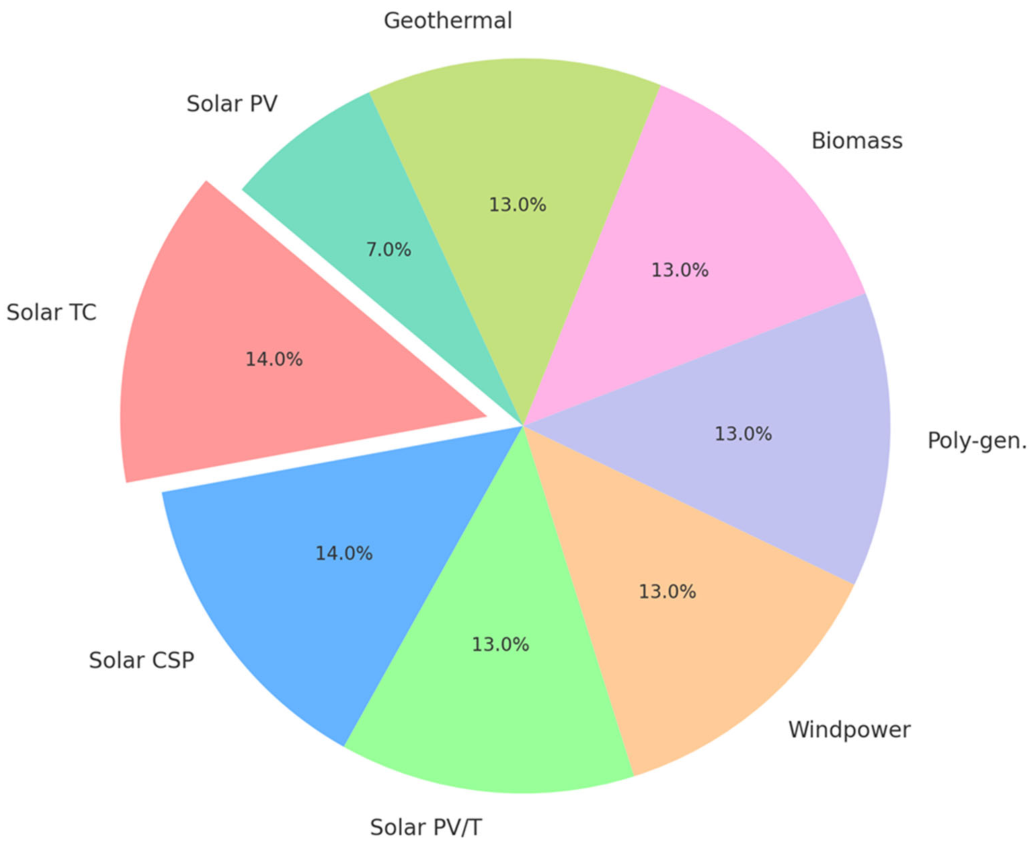


Figure 2. Pie chart representation of energy efficiency in distributed resources.

Figure 3 shows a visual breakdown of CO_2 reduction percentages according to various distributed energy resources over selected years. Notably, the integration of combined heat and power (CHP), micro-hydro, photovoltaics (PV), and wind turbines (WT) between 2013 and 2019 has led to a highest recorded reduction of 97%. In contrast, standalone PV systems in the same period achieved a modest reduction of 13.4%. The assortment of colors differentiates each energy resource combination, enhancing the graph's clarity and allowing for immediate visual comparison of their respective impact on CO_2 reduction across different time spans. This graphical representation underscores the significant potential of diversified energy resource integration in contributing to CO_2 mitigation efforts within the evaluated periods adherence. The CHP technology exhibits the smallest reduction percentage at 10%, while PV demonstrates a reduction of 13.40% and HP exhibits a reduction of 16%.

Figure 4 shows the percentage of CO_2 reduction achieved through various energy resource combinations across different regions and time frames. The data compare the effectiveness of energy combinations in Europe and the US from 2013 to 2019, and in Spain from 2008 to 2010. It shows that the combination of CHP, micro-hydro, PV, and wind turbines (WMT) in the US between 2013 and 2019 achieved the highest CO_2 reduction of 97%. This is significantly higher than any other combination or region shown, including Europe's PV and CHP combination, which resulted in a 28.3% reduction, and Spain's CHP implementation, which achieved a 40% reduction from 2008 to 2010. The US's CHP alone during 2014–2016 shows the lowest reduction of 10%. Each bar is color-coded to visually differentiate between the data points, making it easy to compare the impact of each energy resource combination on the CO_2 emissions' reduction.

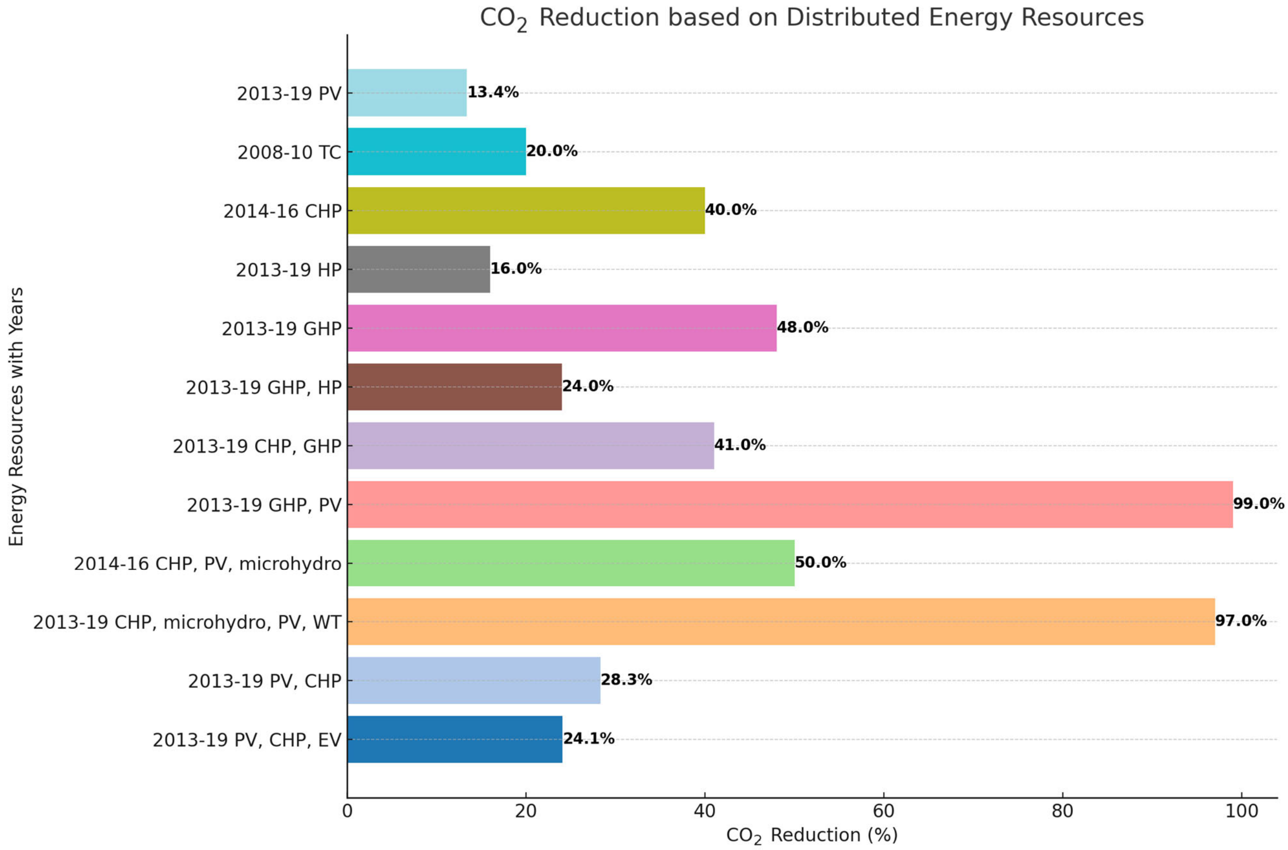


Figure 3. Year-wise CO_2 reduction based on distributed energy resources.

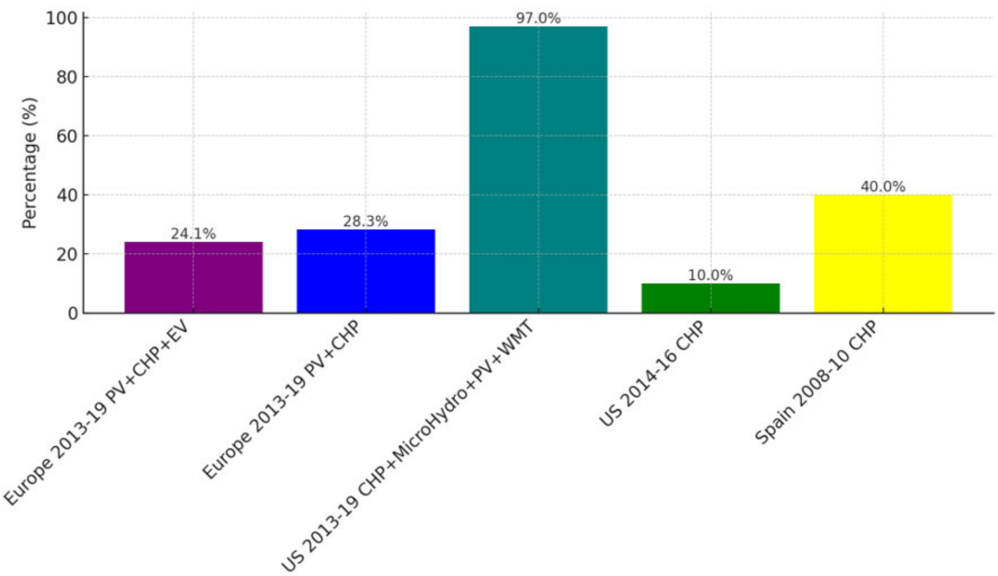


Figure 4. Percentage of supplied energy based on distributed energy resources.

2.3. Integrating Smart Building Technology into Energy Systems

This section attempts to highlight the critical role that smart building technology plays in maximizing the efficiency of modern power generation systems. Many aspects of smart building integration are covered in detail, including the following:

One important component that clarifies how these automated systems intricately connect with energy generation methods are Automation and Control Systems. By reacting instantly to data from sensors and dynamically modifying energy production or storage in response to variations in demand, they play a vital part in controlling energy usage [45]. In order to optimize power generation systems, real-time data on occupancy, environmental conditions, and energy consumption is provided by sensors, which make sensor technology integration crucial [46].

Furthermore, the role of energy-efficient infrastructure in smart buildings provides examples of how a building's construction, materials, and design can minimize energy use and maximize the use of generated electricity [47]. The use of data analytics and optimization is explained in depth in [48], emphasizing how data are gathered and analyzed to estimate energy requirements and optimize patterns of energy production and consumption. Additionally, this section highlights how smart buildings affect grid resilience by explaining how they are bidirectional in terms of both supplying and consuming energy, which helps to maintain the stability of the grid as a whole [49].

Additionally, the incorporation of cutting-edge technologies like artificial intelligence (AI) and machine learning is discussed, along with how they may be used to optimize energy systems, make predictive adjustments, and learn from trends in energy consumption [50]. By including these elements, this section seeks to provide a thorough understanding of the ways in which smart building technology integrates with and impacts modern power production systems, highlighting its critical role in the effective management and use of energy resources. Table 2 shows how smart building technologies intersect with various energy generation methods.

Table 2 illustrates the ways in which different energy generation techniques and smart building technologies interact, listing the techniques and technologies employed as well as their benefits, drawbacks, and citations, for further information.

Table 2. How smart building technologies intersect with various energy generation methods.

Applications	Methods, Techniques, and Technologies	Advantages	Disadvantages	Ref.
Smart Buildings and Solar Panels	Integration of solar panels into smart building architecture, combined with data analytics and sensors for optimizing energy consumption	- Reduces reliance on conventional grid-based electricity - Lowers energy costs through self-sufficiency	- Initial installation costs	[51,52]
Wind Turbines in Smart Buildings	Utilization of wind turbines in smart building design and infrastructure to capture wind energy for localized power generation	- Taps into renewable energy sources for on-site power generation - Reduces environmental impact through clean energy production	- Space and zoning restrictions	[53,54]
Biomass Systems' Integration	Incorporating biomass systems to produce heat and power within smart buildings, leveraging sustainable fuel sources such as wood chips or organic waste materials	- Uses eco-friendly fuel sources for energy production - Reduces carbon emissions	- Fuel sourcing challenges, may emit air pollutants	[55,56]
Geothermal Energy Applications	Employing geothermal systems within smart buildings to utilize the Earth's heat for heating and cooling, reducing reliance on traditional HVAC systems	- Provides consistent, stable energy for heating and cooling purposes - High efficiency due to constant ground temperature	- High installation costs, requires suitable geological conditions	[57,58]

A key component of improving energy efficiency in the context of modern power generation systems is smart building technology. These structures use state-of-the-art techniques in their creative design to control their HVAC (heating, ventilation, and air conditioning) systems. With the use of AI-driven algorithms, these intelligent systems, which are outfitted with sensors and automation, adapt dynamically to occupancy patterns and environmental factors in order to optimize energy use and reduce waste [59,60]. These systems use data analytics to handle large amounts of real-time data from embedded sensors and extract useful insights. By reducing needless use during their empty hours and producing significant energy savings, machine learning techniques assess trends in energy usage and adjust the HVAC and lighting systems accordingly [61,62]. Additionally, smart buildings play a major role in distributed generation systems' grid resilience. These buildings serve as grid nodes, enabling two-way energy flow and their ability to both consume and return excess energy to the grid. They improve the flexibility of the grid during times of peak generation, balancing energy loads and pulling power in situations where the demand is high. The incorporation of cutting-edge technologies like blockchain, AI, and machine learning enhances energy management in smart building systems. Accurate energy demand forecasting and the deployment of self-learning systems that continuously optimize energy use based on changing patterns and occupant behavior are made possible by AI and machine learning [63,64]. Peer-to-peer energy sharing is made possible by blockchain technology, which guarantees safe and transparent energy transactions. This lowers operating costs and boosts overall efficiency [65,66].

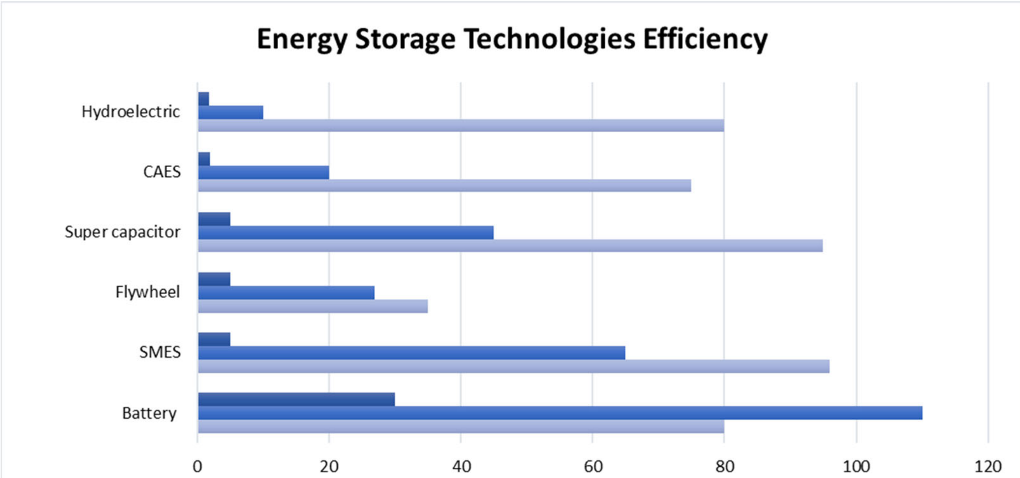
3. Contemporary Energy Storage Solutions

Energy storage systems (ESSs) are essential components of the smart building paradigm that have a large impact on energy management since they make it easier to combine renewable energy sources and manage demand responses. These systems play a crucial role in keeping smart cities' sustainable energy ecosystems in place. In order to maintain a balanced net load profile, energy storage systems (ESSs) efficiently store excess clean energy from renewable sources during times of low demand and make it available during peak demand. Additionally, in smart buildings, ESSs take part in demand response programs, regulating energy consumption locally and efficiently meeting the unique energy needs arising from DC buildings and electric vehicles (EVs) [66,67].

3.1. Energy Storage Technologies' Solutions in Smart Buildings

Batteries serve as pivotal storage devices for electrical energy within the context of smart buildings. Employing various chemical processes, these technologies effectively store energy as chemical energy and have become integral to powering and managing the energy needs of modern smart building applications, as shown in Figure 5. Traditional systems like the mature lead–acid (Pb-acid) and more contemporary options such as sodium–sulfur, sodium–nickel chloride, and lithium-ion batteries exhibit distinct characteristics. Despite their widespread use, batteries inherently come with limitations—higher costs, potential environmental risks, restricted operational lifespans, and limitations to their voltage and current.

A shift in recent years has seen significant decreases in the cost of battery chemistries, promising a more cost-effective and sustainable future. However, within smart building frameworks, where rapid responses and condensed energy discharge are critical, alternative technologies like superconducting magnetic energy storage (SMES), supercapacitors, and flywheels play essential roles. SMES utilizes a substantial superconducting coil specifically designed to accumulate electrical energy within a magnetic field generated by a direct current (DC) flow. Supercapacitors, in contrast, serve to quickly charge and discharge energy at high currents, emphasizing their use in improving grid stability and power quality. Flywheels operate as mechanical rotational devices intended for kinetic energy storage.



	Battery	SMES	Flywheel	Super capacitor	CAES	Hydroelectric
Response Time (ms)	30	5	5	5	2	1.8
Energy (wh/kg)	110	65	27	45	20	10
Efficiency	80	96	35	95	75	80

Figure 5. Energy storage technologies analysis based on Response Time. Energy and Efficiency.

Within the realm of smart buildings, these advanced energy storage technologies have significantly longer lifecycles but come at a higher cost than conventional batteries. Additionally, their provision of energy is limited to very short durations. This is where hydroelectric storage, often known as hydro-pumping storage, steps in. This methodology harnesses the latent energy present in water, transferring it from lower to higher elevation reservoirs, before it is subsequently utilized for electricity generation via turbine channels.

However, despite its widespread use by utility firms and system operators to balance electrical loads, the limitations of these systems become apparent in smaller-scale applications due to their substantial unit sizes and the constraints imposed by terrain and environmental factors [8,68].

In the context of smart buildings, the suitability of energy storage systems (ESSs) varies depending on factors such as their response time, power or storage capacity, physical dimensions, and cost. Therefore, categorizing these systems into three primary discharge categories—bulk storage, distributed generation (DG) storage, and power-quality storage—becomes critical for load balancing, integrating decentralized renewable sources, and ensuring reliable power quality within smart buildings [69].

Additionally, to cater to the thermal energy needs of smart residential and commercial buildings, thermal storage systems play a significant role. They utilize reservoirs containing fluids to accumulate thermal energy for future usage, notably in water tanks within smart cities. Recent developments in molten salt tanks have emerged, particularly in large-scale applications, enabling the storage of high-temperature thermal energy for electricity generation, especially in concentrated solar power plants within smart building infrastructures [70,71].

3.2. Advancements and the Integration of Contemporary Energy Storage Systems (ESS)

Energy storage systems (ESS) have been the subject of several technological advancements and applications in a wide range of industries. Understanding the variety of the technologies and scales involved is essential to comprehending the adaptability of ESS. For instance, the study [72] examines the economic viability of Compressed-Air Energy Storage (CAES) to improve wind energy integration into the German power grid, with an emphasis on a more comprehensive, macroscopic perspective. On the other hand, research on battery-centric systems for the integration of renewable energy is a common focus [73]. Apart from the integration of renewables, research efforts have focused on using alternative energy source technologies to address power quality challenges. Similarly, the study [74] presents an analysis of a wind–diesel power system designed for isolated microgrids and including flywheel storage as a means of energy storage. Another study, ref. [75], thoroughly examines the use of super-capacitor banks in the context of load frequency management in power systems.

The notion of hybrid storage systems, which integrate many storage technologies, presents a persuasive strategy to overcome the limitations of individual devices and enhance their overall effectiveness. The benefits of hybrid energy storage systems (ESS) in the context of microgrids are discussed in detail in [76]. Moreover, the study [77] suggests a hybrid arrangement that combines flywheel and battery components created especially for electric vehicle (EV) applications, emphasizing the importance of power electronics and control strategies. The effective management of charging and discharging protocols for EV fleets is at the forefront of research concerning the use of energy storage systems (ESSs) in plug-in electric vehicles (EVs) [78]. This research looks at the different approaches used in smart charging and highlights the benefits and drawbacks of both decentralized and centralized control systems. Furthermore, a great deal of research has been conducted in [79,80] to evaluate the effects of a large rise in EV adoption on real-world distribution areas and how it might affect energy prices. The distribution of heat generation is also taken into account in these investigations.

One novel strategy described in [81] is to use retired EV batteries as fixed energy storage units for a microgrid, which prompted a detailed analysis of the project's economic viability. Furthermore, the study [82] offers a thorough model that addresses lithium-ion battery deterioration in the context of electric vehicles and suggests charging strategies that maximize battery life. Developments in thermal storage systems have mostly concentrated on maximizing and effectively controlling the thermal energy inside of building structures. In the study [83], the authors describe a complex predictive control system for water thermal storage, while another study [84] shows an electric thermal energy storage system (ESS) controlled by signals connected to energy cost changes. Moreover, contemporary studies make clear that the inclusion of thermal storage is intended for both residential and commercial use, which is frequently connected to solar thermal collectors and co-generation systems [83,84].

Table 3 presents a comprehensive compilation of the cases analyzed in this particular section. The presence of various focal points within each study is apparent, with two primary areas of focus standing out: the incorporation of renewable energy (including evaluations of power quality and supply security) and the integration of electric vehicles (EVs), which also explores the impact on the power grid and the dynamics within the vehicle-to-grid (V2G) framework. The table provides an overview of the applications and tools pertaining to distributed power generation systems. The applications encompass a range of technologies, such as solar power, geothermal heat pumps, poly-generation, and software tools like HOMER and DERCAM.

Table 3. Applications and tools for distributed power generation systems.

Study	Focus	Energy Storage Technologies Explored	Applications and Benefits	Merits	Demerits
[36]	Renewable Integration and Demand Response	Batteries, SMES, super-capacitors, flywheels	Load balancing, peak demand reduction, power quality enhancement	Enhanced grid stability, cleaner energy	High upfront costs, limited storage capacity
[40,44,85]	ESS Utilization Scenarios	Battery storage, DG storage, power-quality storage	Load balancing, renewable integration, power quality enhancement	Diverse application options, improved reliability	Technology limitations, scalability challenges
[41]	Battery Chemistries	Lead–acid, sodium–sulfur, sodium–nickel chloride, lithium-ion	Energy storage, various applications	Well-established technology, declining costs	Environmental concerns, operational lifespan
[42]	SMES, Super-capacitors, Flywheels	SMES, super-capacitors, flywheels	Grid stability, rapid energy release	Extended lifecycles, high reliability	High costs, limited energy provisioning
[43]	Hydroelectric Storage	Hydro-pumping storage	Load balancing, utility-scale energy storage	Large-scale energy storage, reliable	Limited suitability for smaller applications
[38,39]	Hydrogen and Compressed-Air Energy Storage	Hydrogen-based energy generation, CAES	Clean energy source, utility-scale storage	Low emissions, potential for large-scale storage	High production costs, technical challenges

4. Contemporary Infrastructure for Utility Grids

This study primarily centers on the concept of "infrastructure", with a particular emphasis on metropolitan power networks. Aside from the smart grid concept's limitations, which are mostly focused on electric energy, district energy networks are noteworthy instances of smart infrastructure. These networks provide connected structures with an efficient thermal and electrical energy supply [86], offering a solid model for all-encompassing energy management. These districts serve as examples of smart building architecture, displaying state-of-the-art infrastructure for controlling multiple energy sources in urban settings. One of the most important aspects of energy management is demonstrated by its integration into the larger energy grid.

In cities, the electrical grid plays a crucial role in providing the necessary infrastructure for the distribution of energy from power providers to end consumers while ensuring dependability and regularity. However, there are technical obstacles that traditional grids can face, like one-way security measures, restricted communication infrastructure, and control systems. Furthermore, they may find it difficult to deal with the introduction of distributed generation (DG) and rising demand. In order to minimize wasteful spending, research frequently explores methods to improve the effectiveness of the current grid infrastructure [8]. Much like the notion of a smart city, there are multiple ways to define a smart grid infrastructure. Essentially, bidirectional real-time communication between all entities is made possible by the integration of contemporary information and communication technology into a smart grid. It is anticipated that every system and gadget in the smart grid will offer data on the energy it produces or uses. Additionally, these systems must adhere to the rules that specify load scheduling according to variables such the system load, cost, and contractual duties [87].

A smart grid has some fundamental characteristics [88]. It can accommodate growing customer demand without needing more infrastructure to be developed. It uses a self-recovery mechanism and a resilient design that can endure natural calamities and attacks. Additionally, it gives priority to high-quality power supply by utilizing a single power-source design that includes independent energy networks, or microgrids. These microgrids can function independently when necessary, but they can also share electricity among themselves. Most importantly, this project requires immediate communication between all parties, allowing them to carry out their responsibilities effectively and, in the case of smart buildings, greatly assisting in the grid infrastructure's energy management.

Impact of Smart Buildings on Energy Optimization Solutions

Scholarly investigations concerning smart grid matters encompass a wide range of topics, from advanced technological components to regulatory issues. Notably, the topics covered include power electronics, control systems, communication protocols, and commercial tactics. This study focuses on how smart buildings affect energy management in the utility grid's infrastructure, even though it covers a wide range of areas.

Models for long-term investment planning in the smart grid space are one of the most well-known topics in academic literature [6,50,57], and prominently address this topic. These models evaluate the impact of electric vehicles (EVs) and distributed generation (DG) on distribution network investment strategies. Legislation and energy markets suitable for smart grids are frequently the focus of research. Studies, for example, concentrate on demand response programs, energy markets, and regulatory frameworks [55], indicating the importance of comprehending the legislative environment in order to adopt and optimize energy solutions, including those found in smart buildings.

It is important to remember, though, that studies that conceptualize smart grids can overlook technological details. A review of European initiatives has been conducted, including the study by [89], which assessed the application of market price mechanisms in scenarios including smart grids. Furthermore, a thorough analysis of the effects of integrating renewable energies into the grid was conducted by [8]. Research on energy storage and the integration of electric vehicles (EVs) is an area of great interest. Numerous studies have examined the issues that electric vehicles (EVs) present for power systems in the future, including their effects on utility operations and the dynamics of energy market pricing [56]. The management of EV charging stations and regulatory frameworks are proposed and discussed in [59], with a focus on the significance of comprehending different business models and stakeholder roles in the changing grid infrastructure.

Following this, smart metering becomes evident as a crucial step, with [90] highlighting the benefits of sophisticated metering systems in changing consumer behavior and reducing energy use. However, thorough assessments that go beyond possible advantages have also been carried out. These papers discuss the technology's constraints, related hazards, and extant uncertainty [61]. Reliability and power quality are further research topics. Research focuses on how electromagnetic compatibility affects the electrical grid [62] as well as how smart MV/LV substations might improve the power supply dependability in different distribution network topologies [91].

Pilot microgrids have been constructed to model and demonstrate the possibilities of distributed generation technologies and control strategies. They bear resemblance to smart grid properties. One notable example of a smart grid in action is the LABEIN commercial feeder in Derio, Spain, which includes storage units, backup generators, and a variety of renewable energy projects [64]. These projects inevitably touch on the function and significance of smart buildings in relation to the larger framework of energy optimization techniques and utility grid infrastructure.

Table 4 presents a detailed summary of the research cases that have been presented in this section. The process of implementing smart grid infrastructure on a large scale is gradual, as evidenced by the trends identified in the reviewed studies. These technologies are increasingly gaining popularity in various urban areas and have the potential to become widely adopted practices in the future. The table shown herein offers a comprehensive summary of the primary study domains examined under this section, pertaining to the modern infrastructure of utility grids. The subjects addressed encompass many aspects of smart grids: investment planning, regulatory frameworks, the integration of renewable resources and electric cars, smart metering, grid resilience, and microgrid deployments.

Table 4. Overview of key research areas in contemporary smart grid infrastructure.

Ref	Focus	Topics Explored	Findings	Merits	Demerits
[4,8]	Smart Grid Infrastructure	Smart grid attributes, integration of information technologies	Grid optimization, communication, self-recovery	Enhanced demand management, resilience	Technical complexities, infrastructure investments
[55,56]	Key Attributes of Smart Grids	Characteristics of smart grids	Two-way communication, demand flexibility, reliability	Improved energy management, efficient operations	Implementation challenges, cybersecurity concerns
[6,50,57]	Smart Grid Investment Planning	Long-term investment planning for smart grids	Impact of DG and EVs on distribution networks	Efficient resource allocation, cost reduction	Uncertain future trends, regulatory changes
[55]	Regulatory Frameworks and Energy Markets	Regulations and energy markets for smart grids	Facilitating demand responses, market mechanisms	Enhanced demand management, energy efficiency	Regulatory complexities, market uncertainties
[51]	Impacts of EVs on Utility Operations	Impact of EV adoption on energy operations	EV integration, pricing dynamics	Load management, potential revenue streams	Grid stability challenges, infrastructure readiness
[92]	EV Integration into German Grid	Connection of EVs with a specific grid region	EV integration scenarios, grid impacts	Enhanced renewable integration, load management	Grid congestion, technical constraints
[50]	High EV Penetration Effects	Effects of high EV penetration on the power grid	Load equilibrium, energy pricing impacts	Potential load leveling, grid optimization	Grid congestion, stability concerns
[52,53]	Repurposing Retired EV Batteries	Utilization of retired EV batteries for storage	Economic viability, battery degradation	Energy storage options, cost-effectiveness	Battery performance degradation, complexity
[18,54,93]	Thermal Storage Systems	Thermal energy storage in buildings	Peak shaving, thermal requirements	Energy efficiency, comfort management	Retrofit limitations, integration challenges

Table 4. *Cont.*

Ref	Focus	Topics Explored	Findings	Merits	Demerits
[4,8]	Smart Grid Infrastructure	Smart grid attributes, integration of information technologies	Grid optimization, communication, self-recovery	Enhanced demand management, resilience	Technical complexities, infrastructure investments
[6,50,57]	Smart Grid Investment Planning	Long-term investment planning for smart grids	Impact of DG and EVs on distribution networks	Efficient resource allocation, cost reduction	Uncertain future trends, regulatory changes
[64]	Microgrid Deployments	Pilot microgrids with smart grid attributes	European microgrid deployments demonstrate distributed generation and control mechanisms		

5. Smart City Energy Modeling and Integration in Residential and Commercial Buildings

In this study, "residential building" refers to a wide range of structures, including small-scale infrastructure and both commercial and residential buildings. Interestingly, the industrial sector—which is usually located outside of cities—is not included in this classification. Buildings in urban environments are major energy users and a major source of greenhouse gas emissions; in fact, buildings account for around 75% of emissions in urban settings [3]. As a result, one of the main reasons for the focus on smart buildings is the difficulty of lowering energy use while maintaining occupant comfort [68].

The first step in solving the energy consumption conundrum is to put effective control mechanisms for the building energy systems in place. Without requiring changes to the hardware design or building's construction, enhanced operation and management techniques can produce energy savings of 20% to 30% [65]. Demand response is one of the main subjects discussed in scholarly circles here. At the moment, the majority of buildings are passive energy users. In order to reach energy targets, buildings must transition from passive energy consumption to active involvement in the power system. Demand response programs backed by microgrids, improved information and control systems to track loads and energy usage, and the introduction of distributed generation and energy storage technologies are all necessary to bring about this change [55].

The literature on microgrids offers a range of options that are categorized based on application type and scale. The idea of nanogrids appears at a smaller scale, from single homes to small building clusters. According to [66], nanogrids are independent DC power systems that use energy storage systems (ESS) and distributed generation (DG) to continuously supply power to localized loads. The study [65] provides proof of the integration of AC power systems in some nanogrid approaches. Diverse technologies efficiently address energy needs in medium-scale areas, such as districts or communities. As an example, district energy networks supply the energy consumed in a particular district from a central source to meet the needs of both residential and business users. Cogeneration systems have historically been used for heating, but recent developments in the field have allowed them to also generate electricity and cool air [4].

An additional strategy is provided by passive systems, which effectively collect, store, and distribute thermal energy inside a building. The building envelope—which is made up of thermal insulation, mass, window configurations, glazing type, and shading—is taken into account when evaluating the performance of a building. However, there may be significant retrofitting expenses associated with adopting these adjustments in older structures [67].

Advanced Approaches in Smart City Energy Modeling and the Integration of Residential Buildings

The field of control systems and home automation, often known as demotics, has witnessed a great deal of research with the goal of maximizing comfort and energy efficiency. The study [67] provides a full examination of the control systems used in smart buildings, emphasizing energy consumption management and indoor comfort enhancement. Nevertheless, the analysis leaves out information about energy production and storage. Notably, HVAC systems (heating, ventilation, and air conditioning) receive a lot of attention within these disciplines. As an illustration, the study [67] presents an adaptive fuzzy controller designed especially to improve temperature comfort. Furthermore, the combination of HVAC systems, lighting control, and appliance management creates complex information architectures [69]. Notable advances in the fields of demand response and microgrid research have been made recently. Particular developments in power electronics for use in nanogrid applications are discussed in detail in [70], with a focus on the construction and control of voltage-source inverters specifically intended for direct current (DC) systems. The paper presents a mathematical programming approach that combines continuous and integer variables to optimize energy expenses within a building. It also examines various strategies for setting up renewable energy sources and storage systems. It takes dynamic energy pricing and consumption trends into account.

The studies [71,93] look into how district energy networks handle thermal load, with an emphasis on combining electricity, cooling, and heating systems to improve total energy efficiency. Moreover, another study [72] provides a thorough assessment of the important turning points and difficulties associated with the widespread application of microgrids in commercial contexts. A great deal of study has been conducted on passive systems, namely on the building envelope, and the results have been impressive in terms of energy savings, especially when it comes to heating and cooling. For example, the authors in [67] carry out an ecological assessment of three different wall envelope designs, taking into account different temperature conditions and looking at the financial advantages of each design. Comparably, the study [73] examines how hot and muggy environments affect various thermal insulation strategies, window layouts, and shading tactics. In the study by [74], the effect of window design on a hotel construction is examined through the use of simulations. In order to attain cost-effectiveness, several of these aspects must be implemented during the construction stage [73,74].

The examples discussed in this section are compiled in Table 5, which is arranged according to the kind of facility studied as well as the pertinent energy systems and generation components. This summary shows that the main goals of smart buildings are energy efficiency improvement, comfort control, and passive system use. Distributed generation control and demand response techniques are at the center of microgrid research. Conversely, district energy networks primarily deal with load management and energy efficiency enhancement. Demand response, the construction of energy-efficient buildings and districts, and communication difficulties are all addressed by a number of European infrastructure and facilities programs [75–88].

Energy optimization in smart cities requires smart city energy modeling, particularly in residential buildings, which are a significant urban energy consumer. The authors in [58,90] highlight the impact of information and communication technology (ICT) and demonstrate how it has a dual effect on energy intensity and carbon emissions. These observations highlight the importance of strategic planning and the critical role that ICT plays in creating smart cities that are both sustainable and energy-efficient.

Table 5. Contemporary state of the art of smart city energy modeling and integration in residential buildings.

Study	Focus	Topics Explored	Findings	Merits	Demerits
[67]	Control Methods for Smart Buildings	Energy and comfort management through control methods	HVAC systems, lighting, appliance management	Enhanced comfort, energy efficiency	Potential complexity, retrofit challenges
[70]	Power Electronics for Nanogrids	Design and control of voltage-source inverters for DC systems	Advancements in nanogrid power electronics	Efficient DC power conversion, localized energy control	Limited scalability, DC system integration
[65]	Demand Response and Microgrid Control	Regulating and scheduling renewable energy sources and storage	Dynamic energy pricing, demand patterns, cost reduction	Flexible energy consumption, grid stability enhancement	Requires robust communication infrastructure
[71,93]	Thermal Load Management in District Energy Networks	Integration of heat, cooling, and power systems in district networks	Enhanced energy efficiency, load management	Optimal energy distribution, reduced waste	Infrastructure investment, complex integration
[73,74]	Building Envelope Strategies	Influence of wall envelope designs on energy efficiency	Economic advantages, hot and humid environments	Improved thermal insulation, reduced energy loss	Limited applicability to retrofitting
[69]	Information Frameworks for Home Automation	Control over lighting, appliances, and systems	Integration of various smart home features	Increased convenience, energy optimization	Data privacy concerns, interoperability issues
[72]	Microgrid Milestones and Challenges	Commercial adoption of microgrids	Progress, challenges, and future trends	Enhanced energy resilience, local energy control	Initial investment, regulatory hurdles
[75–80]	European Initiatives on Infrastructure and Facilities	Addressing communication, demand response, energy efficiency	Contribution of European projects to smart city development	Collaborative research, knowledge sharing	Fragmented approaches, regional variations
[81–84]	Demand Response and Energy Markets	Market mechanisms, regulations, and services for demand response	Enhancing energy market dynamics and efficiency	Demand flexibility, reduced energy costs	Regulatory complexities, behavior prediction
[85–88]	Energy-Efficient Buildings and Districts	Creation of energy-efficient buildings and districts	Advances in energy-efficient technologies and practices	Lower energy consumption, environmental benefits	Initial costs, design integration challenges

6. Progress in the Energy Usage of Transportation Systems

Sustainable urban growth depends on managing the energy consumption of transportation systems, which are essential to smart cities. The development of transportation systems' energy efficiency in the context of smart cities is covered in this section. We will explore current developments, major issues, and the use of cutting-edge technologies to improve energy efficiency. Table 6 shows energy usage for transportation systems.

Transitioning to electrification and alternate fuels propels the advancements in energy-efficient transportation. Electric vehicles (EVs) are becoming more and more popular because they provide lower carbon emissions, better air quality, and greater energy efficiency. They are becoming easier to access, and this change has a big impact on lowering the environmental impact of urban transportation. Concurrently, smart cities have adopted programs like e-bikes and powered public transportation, proving that environmentally friendly mobility is feasible.

Still, there are a few issues to be resolved in order to fully utilize these improvements. A number of issues, including range anxiety, the scarcity of charging infrastructure, and possible effects on the electrical system, are impeding the widespread adoption of electric vehicles. Furthermore, implementing new technology requires infrastructure changes and large upfront investments. In order to guarantee a seamless transition, policymakers must take regulatory frameworks and public approval into account.

Creative approaches are being used to address these challenges. Improving electric vehicles (EVs) necessitates advancements in battery technology, including energy density and charging speed [90]. Fast-charging networks resolve range limitations [91], while vehicle-to-grid integration enhances grid stability [92]. IoT-driven data analytics optimize traffic flow, reducing energy usage [94].

These innovations find broad applications, transforming private and public transportation. EVs epitomize urban sustainability, in collaboration with electrified public transit and e-bikes [95]. Smart traffic management, Mobility-as-a-Service (MaaS), and integrated mobility platforms minimize energy use, promoting efficient urban transport [96].

In conclusion, significant progress improves smart city transportation's energy efficiency. Electrification accelerates, revolutionizing urban mobility. A comprehensive approach, addressing behavior, regulation, and technology [97], will shape the future of energy-efficient transportation amid persistent challenges.

Table 6. Energy usage for transportation systems.

Aspect	Advantages	Disadvantages	Techniques	Applications
Advancements	Reduced carbon emissions, improved air	Initial costs, infrastructural modifications,	Electrification, hybrid powertrains, smart	Electric vehicles, e-bikes, public transport,
	quality, and energy efficiency.	and public acceptance.	traffic management, autonomous vehicles.	shared mobility solutions.
Challenges	Increased use of electric vehicles,	Insufficient charging infrastructure,	Battery technology improvements, fast	Integrated mobility platforms, urban
	renewable fuels, and shared mobility.	range limitations, and grid impact.	charging networks, last-mile solutions.	logistics optimization, carpooling programs.
Innovations	Electrification, connected mobility	Consumer adoption, policy alignment, and	Vehicle-to-grid integration, real-time	Mobility-as-a-Service (MaaS) platforms,
	solutions, autonomous vehicles.	regulatory frameworks.	data analytics, IoT in transportation.	smart traffic management systems.

7. Energy Modeling Methods for Smart Cities

A key element of the design and management of smart cities is energy modeling. We will thoroughly evaluate the current energy modeling techniques created especially for smart cities in this section. These approaches cover a broad spectrum of instruments and methods for forecasting, evaluating, and optimizing energy production, distribution, and consumption in urban settings. Table 7 illustrates Energy modeling methods for smart cities.

In order to achieve sustainability and resilience, smart cities must prioritize efficient energy modeling and management. These urban landscapes are being subjected to an array of data analytics and optimization methodologies [98,99]. In the context of urban energy models, open data and data analytics are recognized as revolutionary [99,100]. Studies [101,102] have examined urban energy models and talked about the requirements and implementation strategies for using them. The study [103] examined how machine learning might improve the energy management tactics used in smart cities. In the meantime, certain smart cities, like Shenzhen, are looking for low-carbon and sustainable development plans [104]. Numerous studies, including [103,105], examine the infrastructure needed for electric vehicle charging, which is an essential part of the city's energy future. Assessments of the sustainability of smart cities are carried out with the aid of particular indicators and techniques [102]. With a focus on renewable energy applications, sustainable urban planning in smart cities is investigated [105]. Similarly, the study [106] offers an integrated method for urban energy management for sustainable smart cities.

To sum up, energy modeling techniques are essential resources for smart cities. Developments in this area enable towns to lower their expenses, increase their energy efficiency, and meet sustainability objectives. But for these strategies to be implemented successfully, complexity and data management issues must be resolved. Energy systems are planned and run according to a thorough approach, which guarantees that smart cities are both energy- and environmentally efficient.

Table 7. Energy modeling methods for smart cities.

Aspect	Advantages	Disadvantages	Techniques	Applications
Advancements	Improved decision-making, energy cost	Data acquisition and processing challenges,	Data analytics, machine learning, system	Smart city planning, energy-efficient
	reduction, and sustainability.	model complexity, resource-intensive.	simulations, optimization algorithms.	infrastructure design, energy management.
Challenges	Enhanced system complexity, data	Expertise requirements, limited data access,	Integration of heterogeneous data sources,	Microgrid planning, demand-side management,
	accuracy, and scalability.	and interoperability issues.	model validation, real-time data updates.	renewable energy integration.
Methodology	Data-driven analysis, predictive	Lack of standardization, resource-intensive	Data collection, processing, model creation,	Energy master planning, urban development,
	modeling, optimization algorithms.	training, and infrastructure requirements.	validation, scenario analysis, real-time monitoring.	sustainability roadmaps, climate action plans.

8. Conclusions and Policy Implications

This paper has presented a comprehensive survey of the current state of energy management systems within smart residential buildings and their significance within the broader context of smart cities. Throughout the paper, we have navigated the intricate web of connections between power generation, energy storage, infrastructure development, and smart grid systems, underlining their synergetic impact on urban energy efficiency and sustainability. We have observed that smart residential buildings are more than just living spaces; they are critical components that contribute to the intelligent management of urban energy. By employing advanced technologies such as IoT and home automation, these buildings not only enhance the quality of life for their residents but also play a strategic role in the energy ecosystem of smart cities. Our discussion highlighted the importance of integrating distributed generation with renewable energy sources, which are essential for transitioning to a sustainable energy future. While our survey did not venture into analytical or mathematical modeling, it provided a theoretical foundation and a bird's eye view of the myriad of components that constitute the smart city energy landscape. We emphasized the potential of smart transportation systems and their role in reducing urban carbon footprints, showcasing how innovation in this sector is critical for advancing urban sustainability. As urban areas continue to grow, the need for a holistic approach to energy management becomes increasingly apparent. Our study calls for interdisciplinary collaboration and innovation to harness the full potential of smart energy systems. It is imperative that future research continues to build upon the insights presented here, with a focus on empirical analysis and model development to further refine and optimize energy management strategies. In conclusion, this survey serves as a starting point for policymakers, researchers, and industry practitioners to foster sustainable urban environments. The vision outlined herein for smart residential buildings and their interplay with urban energy systems paves the way for a more sustainable, efficient, and intelligent future for cities around the world.

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