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Review

Comprehensive Review of Building Energy Management Models: Grid-Interactive Efficient Building Perspective

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Abstract: Energy management models for buildings have been designed primarily to reduce energy costs and improve efficiency. However, the focus has recently shifted to GEBs with a view toward balancing energy supply and demand while enhancing system flexibility and responsiveness. This paper provides a comprehensive comparative analysis of GEBs and other building energy management models, categorizing their features into internal and external dimensions. This review highlights the evolution of building models, including intelligent buildings, smart buildings, green buildings, and zero-energy buildings, and introduces eight distinct features of GEBs related to their efficient, connected, smart, and flexible aspects. The analysis is based on an extensive literature review and a detailed comparison of building models across the aforementioned features. GEBs prioritize interaction with the power grid, which distinguishes them from traditional models focusing on internal efficiency and occupant comfort. This paper also discusses the technological components and research trends associated with GEBs, providing insights into their development and potential evolution in the context of sustainable and efficient building design.

Keywords: grid-interactive efficient buildings; building energy management models; smart buildings; intelligent buildings; green buildings; zero-energy buildings; demand-side management; energy flexibility

Citation: Bayasgalan, A.; Park, Y.S.; Koh, S.B.; Son, S.-Y. Comprehensive Review of Building Energy Management Models: Grid-Interactive Efficient Building Perspective. *Energies* **2024**, *17*, 4794. https://doi.org/10.3390/en17194794

Academic Editor: John Boland

Received: 10 August 2024
Revised: 19 September 2024
Accepted: 23 September 2024
Published: 25 September 2024

1. Introduction

Building energy consumption is a significant consideration in the current global energy landscape. Building operations constitute about 55% of the global electricity demand. To achieve the Paris Agreement goals, the energy usage of buildings must be reduced by 45% by 2030, a rate that is five times faster on an annual basis than that achieved over the past few years [1,2]. The substantial energy requirements of buildings underscore the critical role that buildings play in overall energy demand and highlight the necessity for advanced energy-management strategies and technologies to optimize energy use in buildings. Traditional building energy management models have primarily focused on reducing energy costs, improving building efficiency, and achieving carbon neutrality at the building level, considering the targets of the building and construction industry.

Numerous approaches have been developed to create building energy models, each with distinct viewpoints and methodologies. These approaches encompass various aspects, such as energy efficiency, sustainability, renewable energy, and demand response. However, energy management has largely been handled within the larger premise of building management models. These diverse models have led to the creation of various terminologies and classifications to represent advanced building models. Intelligent buildings (IBs) are typically defined as those that utilize advanced technologies, automation, and control systems to create a productive and cost-effective environment. IBs are characterized by the integration of advanced technologies, utilizing sophisticated automation and control systems to enhance efficiency and functionality [3,4]. Smart buildings (SBs) build upon this concept, aiming to enhance both operational efficiency and occupant comfort [5]. Green buildings (GBs) prioritize environmental sustainability by incorporating eco-friendly materials and energy-efficient systems. These buildings aim to reduce resource consumption, minimize waste, and lower greenhouse gas emissions [6,7]. Zero-energy buildings (ZEBs) aim to achieve net-zero energy consumption by balancing energy use with renewable energy production on-site [8]. However, these models were proposed and led mainly by experts from the construction sector. These models were timely, represented the goals of the construction sector clearly, and included energy management as part of the entire vision. The recent widespread availability of distributed renewable energy resources has prompted power grid operators to start focusing on utilizing buildings as a grid resource.

Recently, a new trend toward grid-interactive efficient buildings (GEBs) has emerged, emphasizing a balance between the supply and demand of building energy, as well as system flexibility and responsiveness. The growing focus on GEBs reflects efforts to integrate smart technologies, demand-side management, and distributed energy resources (DERs). These measures not only reduce energy consumption but also enhance the flexibility and efficiency of energy use in buildings. The U.S. Department of Energy (DoE) has introduced the concept of GEBs as a strategic initiative to improve the energy efficiency and responsiveness of buildings. This proposal aims to leverage advanced technologies, such as smart control and DERs, to create buildings capable of dynamically interacting with the electrical grid. Unlike earlier approaches that adopt a holistic view of building energy management, GEB models prioritize two key objectives: (1) reducing the building's energy load and (2) enhancing the building's interaction with the power grid. This goal-oriented approach contrasts with conventional models that view energy management as one of many aspects of complex building operations.

This study identifies and elaborates on the following pivotal conceptual elements:

- Provide an in-depth examination of GEBs within the broader framework of existing building energy management models such as IBs, GBs, SBs, and ZEBs.
- Present a comprehensive overview and comparative analysis of literature trends related to GEBs with four key features: efficient, connected, smart, and flexible, based on research published between 2019 and 2023.
- Dissect the four key attributes of GEBs into eight distinct categories, classified as either "internal" or "external" features, to enable a more detailed exploration of GEB technologies and to provide a clearer comparison with other building models.

This paper provides a comprehensive analysis of various building energy management models, with a particular focus on how the GEBs model differentiates itself from conventional models. Because each building energy management model focuses on many aspects and features, it is difficult to compare models based on a single measure. Therefore, other building energy management models are comparatively analyzed from the perspective of GEBs on the four key features of GEBs: efficient, connected, smart, and flexible. Additionally, we found that these features cannot distinguish the characteristics of GEBs clearly when compared with other models because of the differences in system coverage. Therefore, we split the features into internal and external aspects and analyzed the approach adopted by the models to implement the features. This research offers an overview and compares literature trends on GEBs, following a methodology that covers four distinct characteristics of GEBs. Section 2 defines the primary objectives of various construction models, highlighting their unique characteristics and specific goals. Section 3 provides an in-depth exploration of GEBs, including current research trends and distinctive features. In Section 4, we present eight distinct features to highlight the various aspects of GEB components.

A substantial body of research exists on building energy management models, exploring their characteristics, technologies, and efficiency metrics. For instance, Wangs et al. provide a comprehensive review of these models, with an emphasis on system-oriented approaches designed to enhance building operational efficiency [9]. This contrasts with our concept-based approach, which delves into the underlying principles of building energy management. Lu et al. developed a quantitative evaluation framework for building energy systems, introducing practical tools to assess economic efficiency, independence, and grid interaction [10]. While their work emphasizes practical applications and the development of performance indicators, our research diverges by providing a qualitative analysis based on eight expanded characteristics derived from GEBs. Another study in [11], conducted by Giuseppe et al., compared cooperative and coordinated control strategies using a multi-agent system to optimize energy management across multiple buildings. Their focus on specific control strategies contrasts with our broader conceptual approach, which explores the unique attributes of GEBs compared to other building energy management models. Additionally, a comprehensive review examined various strategies for BEMS, such as model predictive control, demand response, and optimization, with a focus on technological and practical applications within HVAC systems [12]. Our research emphasizes a concept-driven analysis focusing on the internal and external characteristics of GEBs. Moreover, a comprehensive scoping review identified key trends and technologies in energy-management strategies within the building sector, particularly in demand-side management and predictive control [13]. While this review highlights the integration of these strategies into building energy management models, our study distinguishes itself by examining conceptual frameworks across different building types, particularly how GEBs differ in terms of grid interaction, flexibility, and advanced smart technologies, providing a more holistic understanding of building energy management from both internal and external perspectives. Lastly, it is important to investigate the role of flexibility in modern power systems, particularly in adapting to renewable energy sources [14]. This foundational work on flexibility in power systems is complemented by our research, which analyzes how GEBs incorporate these flexibility requirements into building energy management, optimizing both building and grid operations. In summary, while the existing research provides valuable insights into various aspects of building energy management, our study aims to broaden understanding by comparing conceptual frameworks of different building models, focusing specifically on the distinguishing features of GEBs and their potential to enhance a flexible and responsive energy grid. While this work provides a foundational understanding of flexibility in power systems, our research builds on these concepts by specifically analyzing how GEBs incorporate these flexibility requirements into building energy management.

2. Definition and Trends of Building Models

2.1. Definitions of Building Models

Building models have evolved over time and are often defined differently in studies due to the absence of a universally accepted definition. As no clear definitions of the different terms and no agreement between authors are observed in the literature, we adhere to definitions provided by recognized official sources. Additionally, we aim to showcase the features of various building models. Figure 1 illustrates the chronological development and milestones of these models, highlighting key technological and conceptual advancements over time.

Intelligent building: The concept of IBs, introduced in the early 1980s, represents a significant advancement in architectural and technological integration in Table 1. With this approach, buildings extensively employ technologically advanced electronics to achieve the desired results, which essentially involves integrating four primary elements (energy efficiency, life safety systems, telecommunications systems, and workplace automation) into a single computerized system [15]. Definitions of "intelligent building" during this period focused on major technological systems such as building automation, communication, and office automation [16]. An IB focuses on leveraging integrated systems and advanced technologies to enhance operational functionality, efficiency, and sustainability through the automation and seamless integration of its components [15,16]. Current IBs demonstrate greater adaptability to occupant needs, predictive maintenance capabilities, and improved performance through continuous learning and optimization. IBs are characterized by features such as centralized control systems, advanced automation, robust data analytics, and a strong focus on sustainability [17].

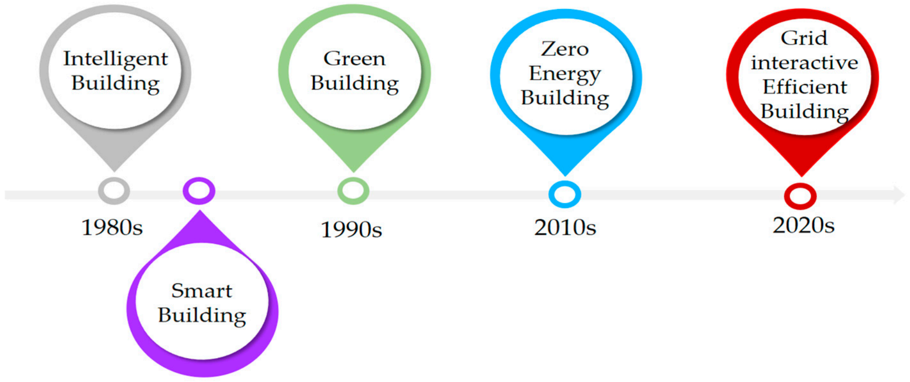


Figure 1. Chronology of building model development.

Table 1. Timeline of definition for intelligent buildings.

Timeline	Source	Definition
1980s	Intelligent Buildings Institute (IBI)	One which provides a productive and cost-effective environment through optimization of its four basic elements, including structures, systems, services, and management and the interrelationships between them [18,19].
1995	Conseil International du Bâtiment Working Groups (CIB)	A dynamic and responsive architecture that provides every occupant with productive, cost effective, and environmentally approved conditions through continuous interaction among its four basic elements, places (fabric; structure; facilities), processes (automation; control; systems) people (services; users), and management (maintenance; performance) and the interrelation between them [20].
1998	European Intelligent Buildings Group (EIBG)	One that creates an environment that maximizes the effectiveness of the building's occupants while at the same time enabling efficient management of resources with minimum lifetime costs of hardware and facilities [16].

Smart building: SBs can be considered a sophisticated advancement within the broader category of intelligent buildings in Table 2. They build on the centralized control and automation aspects of intelligent buildings by incorporating more advanced, interconnected technologies [21]. The terms "smart building" and "intelligent building" have been used interchangeably since the latter concept emerged. Therefore, it is difficult to distinguish between these types of buildings clearly, although efforts have been made to this end [22]. The difference between SBs and IBs lies in their purpose and the functional approaches adopted to achieve the respective goals. While IBs focus on increasing building efficiency by using automated building systems, SBs are adaptable and flexible, with a focus on achieving the optimal combination of occupant comfort level and energy consumption. Advances in artificial intelligence (AI) algorithms and Internet of Things (IoT)-based sensing networks have played a significant role in building energy management and have contributed significantly to the evolution of smart buildings. These technologies enable real-time data analysis, predictive maintenance, and adaptive system response to occupant needs [21,23,24]. Thus, these advancements have promoted the development of buildings capable of learning, decision making, and operational optimization, thereby improving overall building performance and sustainability [22,24–26].

Table 2. Timeline of definition for smart buildings.

Timeline	Source	Definition
2008	Continental Automated Buildings Association (CABA)	An SB has an ability to "figure out behavior and behave according to impacts of parameters around it" [27].
2008	The Climate Group	A suite of technologies used to make the design, construction, and operation of buildings more efficient, applicable to both existing and new-build properties [28].
2020	European Union Commission	Smart buildings are defined by the inclusion of predictive models to optimize performance, anticipate future needs, and ensure sustainability through advanced interoperability [29,30].

Green building: GBs utilize renewable energy sources such as solar, wind, and geothermal power, along with incorporating green roofs, energy-efficient appliances, sustainable construction materials, and water-conservation measures shown in Table 3. The primary focus of these buildings is on mitigating environmental impact through the use of sustainable materials and advanced energy-efficient technologies. As GBs offer an opportunity to minimize the adverse impact of buildings on the environment and occupants, they have recently attracted considerable attention. The introduction of GBs assessment methods has played a crucial role in promoting the construction of GBs. The first of these methods, the Building Research Establishment Environmental Assessment Method (BREEAM), was developed in the United Kingdom in 1990. This was followed by the development of the LEED rating system by the U.S. Green Building Council (USGBC) in 1998, which rapidly became the dominant GB assessment tool worldwide [31].

Table 3. Timeline of definitions and key concepts regarding green buildings.

Timeline	Source	Definition
2005	U.S. DoE	A green building is designed to reduce the overall impact of the built environment on human health and the natural environment through efficient use of energy, water, and other resources; protection of occupant health; and reduction in waste, pollution, and environmental degradation [32].
2005	IEA	A green building is one that consumes less energy, uses resources more efficiently, and has a minimal impact on the environment. It emphasizes renewable energy, reduced water use, sustainable materials, and better indoor air quality [31].

Zero-energy building: ZEBs are designed to significantly reduce energy consumption and carbon emissions by balancing their energy use with energy production from renewable sources. The goal of ZEBs is to minimize energy consumption through the use of energy-efficient technologies and renewable energy sources, such as solar panels, wind turbines, and geothermal systems. These buildings typically feature high levels of insulation, energy-efficient lighting and appliances, and passive solar designs [33]. In addition to being environmentally friendly, ZEBs can offer cost savings over time, reducing energy bills for owners and occupants.

Recent research suggests that the environment friendliness of buildings can be enhanced by connecting them to municipal and regional energy networks that utilize renewable energy sources. This approach aims to enhance the reliability and flexibility of energy supply. By implementing energy-saving measures to ensure that the annual local energy consumption remains below the amount of renewable energy generated locally, more renewable energy can be integrated into existing regional power grids. This integration enhances grid flexibility, allowing consumers to adjust their energy use based on demand and thereby improving energy storage management. To create value and social incentives, sustainable energy sources must be combined with the built environment. This includes the use of renewable energy sources, recycled materials, and advanced technologies such as energy storage, smart energy grids, demand-response systems, cutting-edge energy management systems, user interaction, and information and communication technology (ICT) [34,35]. Table 4 presents the definition related to ZEBs. The IEA defines ZEBs as structures that do not rely on fossil fuels, with all energy requirements being met through solar energy and other renewable resources [36]. In 2010, the European Parliament and the Council of the European Union defined ZEBs as structures characterized by exceptionally high energy performance, where the minimal energy required is primarily supplied by renewable sources generated on-site or in close proximity [37]. The U.S DoE defined ZEBs as a building that consumes less or equal to the amount of energy produced from renewable sources over the course of a year on a primary energy basis [38].

Table 4. Timeline of definitions and key concepts regarding zero-energy buildings.

Timeline	Source	Definition
2008	IEA	ZEBs are buildings whose energy consumption over the course of the year is offset by renewable energy generation. Depending on the definition boundary, the renewable energy generated can be on-site or off-site [36].
2010	EU of the European parliament and of the council	The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby [37].
2015	U.S. DoE	An energy-efficient building where, on a source energy basis, the actual annual delivered energy is less than or equal to the on-site renewable exported energy [38].

Grid-interactive efficient building: In 2019, the U.S. DoE defined GEBs as energy-efficient buildings that use smart technologies and on-site DERs to provide demand flexibility while co-optimizing energy cost, grid services, and occupant needs and preferences in a continuous and integrated manner, as shown in Table 5 [39]. The concept of GEBs has evolved to reflect advancements in building technologies, energy management, and grid interactions. While several researchers and organizations emphasize different aspects of GEBs, they consistently highlight the integration of energy efficiency, smart technologies, and demand flexibility. The definitions converge on the idea that GEBs optimize energy consumption within themselves while actively supporting the electricity grid through dynamic adjustments based on real-time signals and conditions. Additionally, the definitions consistently emphasize the dual goals of optimizing energy costs and providing grid services while maintaining or enhancing occupant comfort and productivity. This trend underscores the continuous and integrated operation of GEBs, balancing energy management with the needs of both building occupants and the electricity grid.

Table 5. Timeline of definitions and key concepts regarding grid-interactive efficient buildings.

Timeline	Source	Definition
2019	U.S. DoE	“GEBs are used as flexible power demand resources to provide grid services” [40].
2021	Research Paper	“Grid-interactive efficient buildings have been considered as an important asset to support the power grid reliability by utilizing the demand flexibility offered by GEBs are enabled by advances in sensors and controls, and the communication between building equipment, whole buildings, and the grid” [41].
2021	Research Paper	“Buildings designed to provide grid services in this manner typically go by the name of grid-interactive efficient buildings or grid responsive buildings” [42].
2021	Research Paper	“GEB builds on the well-established discipline of energy efficiency by adding strategies and technologies to also manage peak demand and coordinate buildings’ electrical loads, taking into account peak usage hours, renewable generation, storage options, and resiliency needs as appropriate” [43].

Table 5. *Cont.*

Timeline	Source	Definition
2023	IEA	"Efficient grid-interactive buildings (EGIBs) are energy-efficient buildings with grid-connected smart technologies characterized by the active use of DERs to optimize energy use and energy flexibility for supporting grid services, occupant needs and preferences, and cost reductions in a continuous and integrated way" [44].
2023	Research Paper	"The concept of GEB envisions building loads actively controlling power consumption in alignment with grid services" [45].
2023	Research Paper	"GEB are structures designed to optimize energy consumption and generation, using advanced technologies that enable two-way communication between the building and electric grid. GEB leverages real-time information on energy prices and grid conditions to adjust their energy consumption and generation, while also considering user comfort and operational requirements" [46].
2023	Green Building Council of Australia	"An energy-efficient building that uses smart technologies and on-site DERs to provide demand flexibility to reduce GHG emissions while optimizing for energy costs, grid services, and occupant needs. A grid-interactive efficient building is capable of providing energy-efficient building services and dynamic grid services through connected, smart control of multiple flexible building loads and DERs" [47].

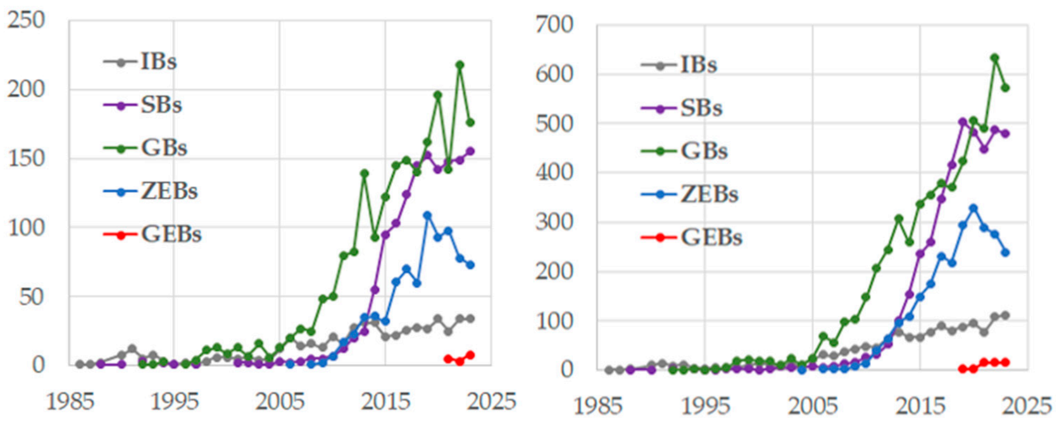
2.2. Definition Summary

Each building model possesses unique characteristics and goals. From the perspective of building energy management, we identify and highlight the key requirements that each of these models prioritizes. These priorities may include optimizing energy efficiency, integrating renewable energy sources, enhancing occupant comfort, or reducing operational costs:

- IBs—utilize advanced computer technology to autonomously control equipment, manage information resources, and deliver user-centric information services. By integrating communication systems, networks, automatic controls, and architectural design, they achieve seamless automation, efficient resource management, and optimal service provision [48].
- SB—focus on the occupants and the high-level interaction with the occupants of a building [49].
- GBs—target environmentally friendly construction practices that contribute to saving energy, water, and raw materials; minimizing water surplus and greenhouse gas emissions; and the reuse and recycling of materials in order to create comfortable, clean, safe, and productive houses [50].
- ZEBs—pursue the reduction in energy demand through energy-efficient technologies and utilize renewable energy sources to supply the remaining energy demand [51].
- GEBs—emphasize interactions with the electrical grid to optimize energy usage and enhance grid stability, often incorporating demand response strategies.

2.3. Trends in Building Energy Management Models

Figure 2 presents the number of research papers on building energy management models published across different categories, as identified through searches in the Web of Science database. The two graphs distinguish between searches based on the "Title" and "Topic" criteria, using keywords such as "Green Building" or "Green Buildings". Figure 2a displays the number of papers with keywords explicitly in the title, while the right graph includes papers where keywords appear in the title, while Figure 2b presents the number of papers where the search terms appear in the title, abstract, keywords, or author keywords. These graphs provide valuable insights into the temporal dynamics of the research interest in and development in building technologies from 1980 to 2025.



(**a**) Title-based search in Web of Science. (**b**) Topic-based search in Web of Science.

Figure 2. Trends of publications on building energy management models from 1980 to 2025.

In both title-based and topic-based searches, intelligent buildings exhibit a relatively flat trend from 1980 until around 2005. After 2005, a significant rise is observed, culminating in a peak around 2019, followed by a slight decline. GBs show slow growth until approximately 2005 in both graphs. Following this period, there is a marked rise, with a peak around 2020 before a slight decline. The decline after 2020 suggests a maturation of the field or a shift in research focus. The trend for smart buildings mirrors that for GBs, with a flat trajectory until the mid-2000s, followed by a steady rise and a peak around 2018. ZEBs showed no significant activity until the mid-2000s before modest growth and peaking around 2018. These trends suggest an increasing interest and investment in achieving net-zero energy performance in buildings in line with policy obligations and environmental goals. Since then, there has been a slight decline, which can be interpreted as a temporarily demand-refining Chasm phenomenon before exiting the initial market and reaching the stage of widespread adoption by the general public. GEBs remain relatively flat, with negligible growth throughout the observed period in both graphs. This indicates that GEBs represent a nascent concept in the literature, highlighting an opportunity for future research and development.

3. GEBs' Key Features

3.1. Key Features of GEBs and GEBs Research Trends

GEBs are capable of providing energy-efficient building services and dynamic grid services through connected, smart control of multiple flexible building loads and DERs [46]. The U.S. DoE has outlined four key characteristics that define GEBs:

1. **Efficient:** GEBs can offer similar or enhanced energy-efficient building services compared to current standards by incorporating features such as high-quality walls and windows, high-performance appliances and equipment, and optimized building designs [40,52].
2. **Connected:** GEBs enable two-way communication between technologies, the grid, and occupants for responding to time-dependent grid needs [46]. This two-way communication capability is essential for effectively addressing the dynamic requirements of the grid [40].
3. **Smart:** GEBs support advanced control of buildings and community energy systems, characterized by several key capabilities, including the ability to co-optimize and adapt various aspects of control over time and to reflect changes in building analytics. Ubiquitous sensing and optimized controls are essential for managing multiple behind-the-meter DERs in ways that benefit the grid, building owners, and occupants [40,52].

4. **Flexible:** GEBs can provide dynamic load control to support the electric grid, including shedding, shifting, and modulating loads, with modulating loads offering ancillary services such as frequency regulation and voltage control. Additionally, building energy loads can be dynamically shaped and optimized through behind-the-meter generation, electric vehicles, and energy-storage systems [40,52].

A comprehensive analysis of various GEB research papers reveals several common aspects that underscore the key focus areas in this field. The primary themes encompass the integration of advanced technologies, demand-side management, and the optimization of energy resources. Numerous studies have explored strategies for demand-side management and demand response, focusing on adjusting and controlling building energy usage in response to grid signals. Keywords such as "demand flexibility", "demand response", and "grid-interactive" emphasize the importance of constructing buildings to be more adaptable and responsive to grid needs [53–55]. The optimization and control of DERs, such as solar panels and energy-storage systems, are critical aspects of GEBs research. Such efforts highlight the importance of integrating these resources within building systems effectively to enhance both energy efficiency and resilience [56–60]. The integration of smart building technologies and building automation systems (BAS) emerges as a significant focus within GEB research. These advanced systems facilitate the automated control of various building operations, thereby enhancing operational efficiency and ensuring greater occupant comfort [59–66]. These common aspects, namely, technological innovation, demand-side management, and DER optimization, form the foundation of GEB research. They point toward a future where buildings not only consume energy but actively manage and contribute to energy systems, thereby improving both economic and environmental outcomes.

Figure 3 categorizes GEB studies into four distinct characteristics. The data indicate a consistent increase in the volume of GEB research over time. Initially, the research predominantly emphasized flexible building technologies, but starting in 2023, there has been a marked shift, with a growing focus on smart technologies and grid-connected systems. This trend suggests that future research will increasingly prioritize grid connectivity, with a growing emphasis on developing and enhancing grid-interactive technologies within the GEBs framework.

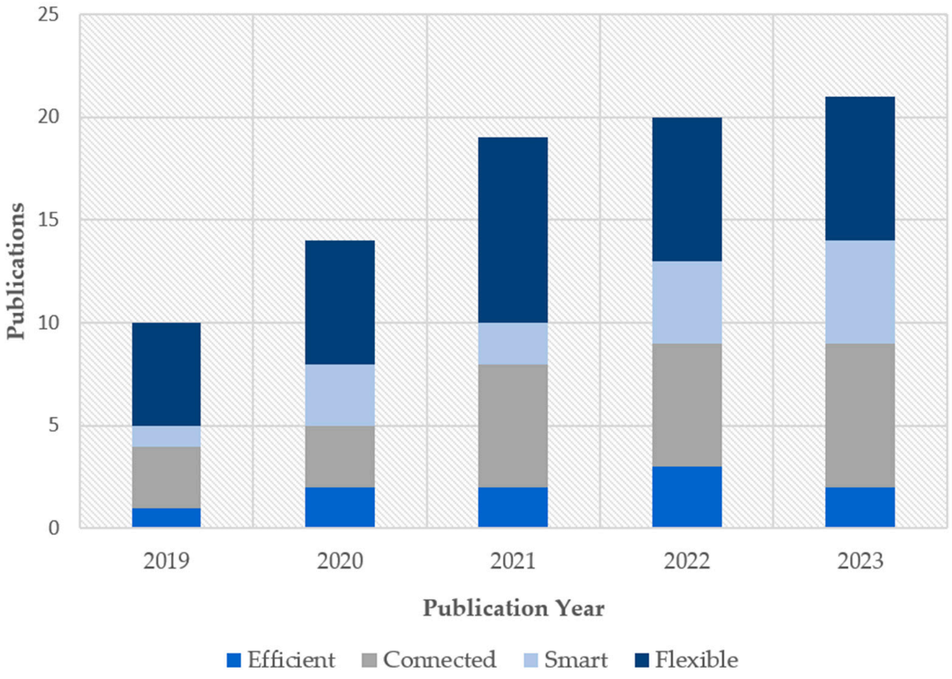


Figure 3. Research publication trend for GEBs.

The GEBs concept was introduced by the U.S. DoE in 2019, although similar ideas were explored in research as early as 2014 [67]. This review specifically analyzes and compares research trends year by year from 2019 onward.

The term "GEBs" first appeared in 2019, marking the onset of associated research activities. This year also witnessed a notable surge in interest in interactive buildings, with a strong emphasis on demand response and dynamic pricing mechanisms [68–71].

In 2020, research activity intensified, with publications focusing on the practical implementation of interactive demand-side management strategies to enhance energy efficiency. The research scope expanded to include adaptation models in energy management and the application of predictive control techniques for grid interaction [64,72–79]. Additionally, there was a deeper exploration into advanced control strategies and adaptive mechanisms for optimizing GEBs' performance [42,79–84].

In 2021, research on GEBs primarily focused on the implementation of advanced metering infrastructure (AMI), with efforts directed toward developing enhanced data-collection and -analysis techniques to improve grid interaction efficiency [82,83]. Studies also focused on advanced control strategies for grid-interactive buildings, with significant attention paid to the application of AI, machine learning, and the IoT to optimize building energy management systems and enhance grid stability [84,85]. Studies also investigated heating, ventilation, and air-conditioning (HVAC) load shedding, and the quantification of demand flexibility was investigated as well [86,87].

In 2022, research focused on benchmarking demand flexibility and establishing robust two-way communication protocols between grids and buildings. Extensive investigations were conducted on phase change materials (PCMs) to enhance load flexibility and building efficiency, as well as on the application of predictive control techniques and simulation modeling for energy flexibility [55,88–90]. The emphasis was on improving the reliability and scalability of grid-interactive solutions, as well as addressing real-world implementation challenges [91,92].

In 2023, research on GEBs was characterized by a strong focus on integrating AI and machine learning for advanced energy management, enhancing cybersecurity and operational resilience, and leveraging demand flexibility through smart technologies. Researchers also pursued robust system modeling and simulation frameworks, assessing the economic and environmental impacts of energy flexibility and developing standardized metrics for consistent evaluation. These trends highlight a concerted effort to adopt innovative technologies and methodologies to optimize building efficiency, improve grid stability, and ensure sustainable and resilient building operations [45,46,53,56,62,65,93–107].

Recent studies have shifted the research emphasis toward developing new optimization techniques and focusing on modeling and simulation for system performance. Key areas of focus also include predictive control and neural network-based models. Additionally, significant attention has been devoted to exploring new business models, policy implications, and the role of GEBs in achieving sustainability goals [60,105,108–116]. In summary, most research on GEBs has focused on enhancing the flexibility and interactivity of building energy systems with the grid.

This work could be advanced in several key areas in future research. Enhancing probabilistic forecasting techniques for renewable energy availability is essential for improving prediction accuracy. The development of adaptive demand forecasting models and the optimization of control strategies for dynamic grid interactions are critical for enhancing the performance and resilience of GEBs. Additionally, the development of adaptive demand forecasting models and the optimization of control strategies for dynamic grid interactions are vital for improving the performance and resilience of GEBs. Addressing these uncertainties is paramount for advancing the effectiveness of GEBs. Recent studies provide valuable frameworks and insights that can inform these advancements. For instance, a distributed cooperative operation strategy for multi-agent energy systems integrated with wind, solar, and buildings based on chance-constrained programming has been proposed [117]. This strategy could significantly enhance the coordination and reliability of distributed energy resources. Furthermore, the development and application of a bi-level optimization model could greatly improve the integration of grid systems with building energy management [118]. Such a model would simultaneously address grid-level strategic decisions, such as pricing mechanisms and demand response strategies, alongside building-level operational decisions. The upper tier of this model would focus on strategic considerations like grid stability and pricing policies. Moreover, there is an urgent need to address contemporary challenges related to demand flexibility, particularly in the context of load shedding and load shifting within demand response programs [84]. Despite its critical importance, research in this area still needs to be improved, hampered by factors such as data limitations and the intricacies of real-time demand management. Advancing research on demand flexibility is crucial not only for optimizing energy consumption and reducing peak loads but also for enhancing grid stability and effectively integrating renewable energy sources.

3.2. Extended Key Factor-Based Comparative Analysis

Although four key factors are mentioned in the previous section, the aforementioned characteristics still have ambiguity in differentiating GEBs from other building models. Herein, in Table 6, we subdivided the four original features into eight distinct features, categorizing them as either "internal" or "external".

Table 6. Subdivision of 4 original features to explore 8 key elements in considering the building energy models.

Features	Internal	External
Efficient	building-efficient	grid-efficient
Connected	intra-connective	grid-connective
Smart	local-smart	grid-smart
Flexible	load-flexible	grid-flexible

First, the concept of "efficient" is bifurcated into "building efficient" and "grid efficient" to distinguish between the internal and global aspects of building efficiency. "Building efficient" focuses on reducing heat loss through advanced technologies such as insulation systems and dynamic windows. This encompasses the optimization of the building envelope, including walls, doors, windows, roofs, and floors, along with the material properties that enhance structural efficiency. Additionally, it involves a sophisticated HVAC system designed to maximize indoor comfort while minimizing energy consumption [119,120]. "Grid efficient" transcends building-level efficiency to provide a global perspective on efficiency. From the grid efficient viewpoint, buildings dynamically interact with the power grid to optimize energy use, enhance grid stability, and reduce peak demand, thereby improving overall grid efficiency. The flexibility of such buildings can lead to increased cost benefits by obtaining the need for generators and transmission lines, thereby enhancing both economic and environmental global efficiency [121,122].

Second, the concept of "connected" is divided into "intra-connective" and "grid-connective". "Intra-connective" refers to the internal connectivity for building management system. This involves the interconnection of integrated systems and infrastructures within the building to support smooth energy flow and management through technologies such as sensors and ICT [123]. "Grid-connective" refers to facilitating bidirectional communication between buildings and the grid. This involves utilizing technologies such as AMI to enable two-way communication between the grid and residents, allowing buildings to respond to the grid's demands over time. Buildings that are interoperable with the grid can receive and respond to near real-time signals from energy suppliers regarding demand conditions, available power, and pricing [124]. However, both forms of connectivity are potentially vulnerable to attacks on the physical layer, transport layer, network operation layer, and application layer. Therefore, they are also closely related to protocols that consider network security [125].

Third, “smart” characteristics are divided into “local-smart” and “grid-smart”; “local-smart” focuses on providing comfort and protection to occupants beyond simply optimizing energy aspects of the building itself [126]. “Grid-smart” refers to the flexible optimization of energy efficiency, flexibility, and occupant preferences by considering both grid and building conditions. It involves monitoring buildings and the grid to perform multi-objective optimization of overall energy use, energy consumption during specific periods, and occupant comfort; thereby, building operations are optimized in line with the grid conditions [127].

Finally, the concept of “flexible” can also be divided into “load-flexible” and “grid-flexible”. The primary difference between these two characteristics lies in the objective behind their flexibility. “Load-flexible” refers to minimizing building electricity costs by managing resources flexibly. It focuses on demand-side management strategies such as load shedding, load shifting, and load modulation to establish a load profile [128,129]. “Grid-flexible”, in contrast, relates to operating buildings flexibly to enhance grid stability and flexibility. It involves participating in demand response markets and ancillary service markets to ensure that buildings achieve grid flexibility [130,131].

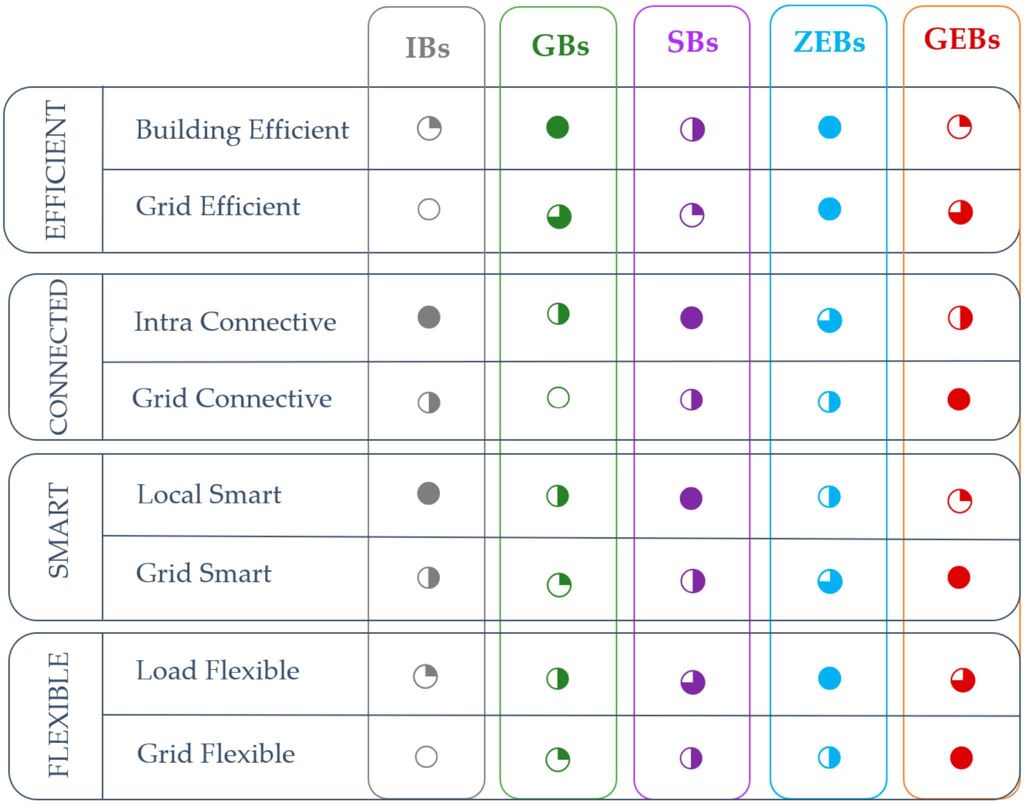
These eight features of building energy management are compared across various building models, and the level of each feature is classified for each model. This comparative analysis aims to provide a comprehensive understanding of how different building energy management models perform in relation to key attributes such as energy efficiency, passive and active design strategies, demand response capabilities, and integration with smart technologies. Construction technologies are becoming increasingly sophisticated, evolving to incorporate a wide range of advanced characteristics. The growing sophistication and versatility of construction technologies are pivotal in meeting the complex demands of modern building projects, which necessitate that structures be not only more resilient and energy-efficient but also capable of adapting to future technological advancements and environmental challenges.

Table 7 presents a comparison of the feature differences between GEBs and other building types; an analysis was conducted using a diagram based on the assessment of the eight key features. Each feature was rated on a scale from 1 to 5, reflecting the degree of emphasis placed on it. Specifically, level 1 models do not consider key concepts explicitly. Level 2 models address key concepts partially. Level 3 models attempt to adopt existing standards or methodologies. Level 4 models apply these existing standards or methodologies but do so by extending or modifying them as per specific needs. Finally, Level 5 models go beyond existing frameworks, presenting new concepts and novel standards or methodologies to advance the field.

Table 7. Evaluation scale for key concepts.

Score	Description
Level 1	No concept
Level 2	Partial concept
Level 3	Adopt existing concept
Level 4	Extend concept
Level 5	Propose novel concept

As described in Figure 4, GEBs place significant emphasis on external and flexible features, in contrast to other building types, which prioritize different aspects. This comparative analysis highlights the unique focus areas of GEBs, underscoring their advanced approach to building management and integration with the grid.



		IBs	GBs	SBs	ZEBs	GEBs
EFFICIENT	Building Efficient	◔	●	◑	●	◔
	Grid Efficient	○	◕	◔	●	◕
CONNECTED	Intra Connective	●	◑	●	◕	◑
	Grid Connective	◑	○	◑	◑	●
SMART	Local Smart	●	◑	●	◑	◔
	Grid Smart	◑	◔	◑	◕	●
FLEXIBLE	Load Flexible	◔	◑	◕	●	◕
	Grid Flexible	○	◔	◑	◑	●

Figure 4. Feature comparison of building models across key concepts.

Figure 5 provides a comparative analysis of various building energy management models, specifically evaluating their grid interactivity across eight key elements. This figure is not intended to rank these models as inherently superior or inferior but to highlight the distinctive characteristics that set GEBs apart from other building types, such as IBs, GBs, SBs, and ZEBs. IBs demonstrate a well-rounded performance, particularly excelling in intra-connectivity and building efficiency. Their high scores in these areas reflect their strong internal communication networks and operational effectiveness, which are critical for optimizing building performance within a self-contained system. GBs, conversely, focus primarily on environmental efficiency, achieving notable performance in building efficiency. This emphasis on sustainability and resource conservation is evident in their design, which prioritizes minimizing environmental impact through efficient resource use and sustainable building practices. Their approach is largely inward-looking, with a primary focus on optimizing the building's internal operations to achieve environmental goals. SBs are characterized by their adaptability and high performance across a range of internal and external metrics. They demonstrate advanced local smart capabilities, strong intra-connectivity, and effective grid-connectivity. These features highlight their sophisticated internal systems and robust integration with external energy networks. This dual emphasis enables SBs to optimize internal operations while effectively interacting with broader energy systems, thereby enhancing their overall flexibility and responsiveness. ZEBs are primarily dedicated to achieving net-zero energy status, which is reflected in their high performance in grid connectivity and grid efficiency. Their design emphasizes balancing energy consumption with on-site energy production, often through the use of renewable energy sources. This focus on energy efficiency and grid interaction underscores their role in reducing the overall energy demand on the grid, making them a critical component in sustainable energy strategies. GEBs are uniquely specialized in their grid interaction with the energy grid. The figure illustrates that GEBs outperform other models in several key areas, including grid flexibility, grid smartness, grid connectivity, and load flexibility. These attributes highlight GEBs ability to dynamically respond to grid signals, adjusting their energy usage in real-time to meet the demands of the grid. This high level of responsiveness and adaptability positions GEBs as a crucial player in modern energy systems, where the ability to interact with and support the grid is becoming increasingly important. Figure 5 underscores that while each building model has its strengths, GEBs are particularly distinguished by their advanced grid-interactive capabilities, which are essential for optimizing energy use and enhancing the overall stability and efficiency of the energy grid.

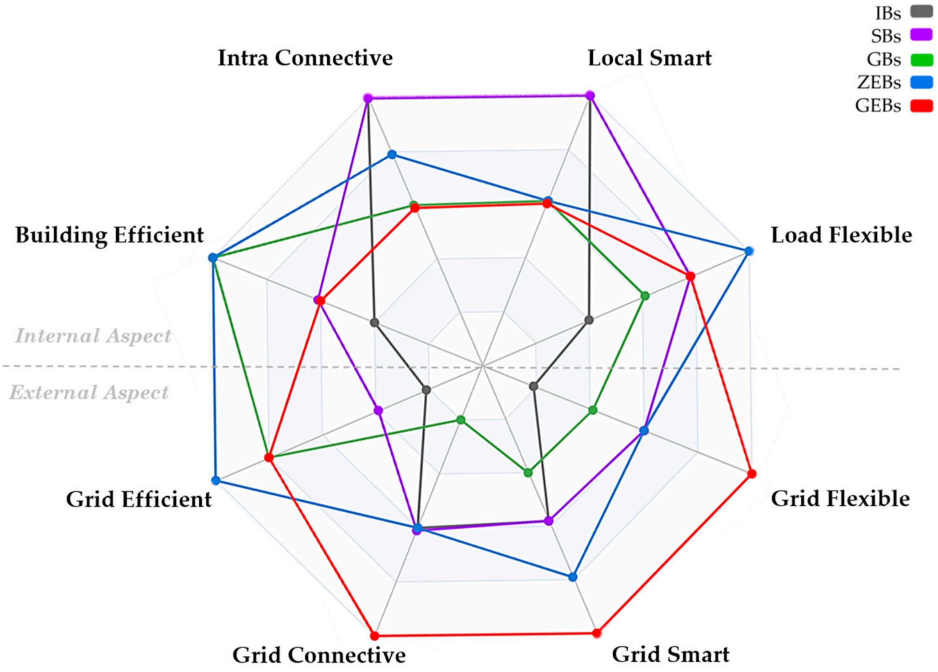


Figure 5. Comparative analysis of building models across eight key features.

4. Technical Components for GEBs

The key components of GEBs are categorized into eight distinct features, classified as either internal or external aspects. This categorization is intended to emphasize the differences between GEBs and traditional building energy systems.

4.1. Key Components for Building-Efficient

Passive: an efficient façade refers to the external part of a building designed to optimize energy performance by reducing heat transfer, enhancing natural lighting, and improving thermal comfort. Efficient façades often include advanced materials such as project management systems (PMS) and smart glass that adjust their properties based on external conditions, providing insulation and reducing reliance on HVAC systems [132,133]. The building envelope encompasses all the elements that separate the interior of the building from the external environment, including walls, roofs, floors, windows, and doors. An efficient building envelope aims to enhance energy efficiency by incorporating high-performance insulation, air sealing, and energy-efficient windows. These components work together to reduce energy consumption by preventing unwanted heat transfer, thereby maintaining a stable indoor climate with less energy used for heating and cooling [134]. However, the distinction from existing efficiency is relatively limited, encompassing both passive and active dimensions.

Active: dynamic airflow systems are those that adjust the ventilation and airflow within a building based on real-time data related to occupancy, temperature, and air quality. Key examples include variable air volume (VAV) systems and demand-controlled ventilation (DCV). VAV systems modulate the volume of air supplied to different zones according to demand, while DCV systems adjust ventilation rates based on sensor data to maintain indoor air quality efficiently. These systems ensure optimal indoor environments while minimizing energy use by dynamically responding to changing conditions [133–135]. Intelligent BMS integrate various building systems, such as HVAC, lighting, and security, to optimize their operation through real-time monitoring and control. These systems leverage AI and predictive analytics to enhance energy efficiency, reduce operational costs, and improve occupant comfort [136].

4.2. Key Components for Grid Efficiency

Grid efficiency extends beyond the energy performance of individual buildings. GEBs adopt a more holistic approach by continuously optimizing both the energy consumption within buildings and their interactions with the broader energy grid. GEBs are designed to adjust operations in real time based on external grid signals, weather forecasts, and energy price fluctuations. This capability enhances operational efficiency, surpassing the performance of traditional building energy management models. These initiatives not only focus on individual buildings but also emphasize the importance of integrating buildings into a more efficient and sustainable grid system. Various international standards, such as the ISO 50001 [137], guide organizations in implementing efficient energy management systems. Advanced building codes that mandate higher energy efficiency standards for new constructions and retrofits contribute significantly to reducing the carbon footprint of buildings globally [138]. Smart grids facilitate the integration of renewable energy sources like solar and wind power, ensuring that buildings can utilize clean energy efficiently [139].

4.3. Key Technologies for Intra-Connective

Traditionally, building communication systems have been designed with a focus on internal communication technologies related to sensors, networks, the IoT, protocols, and security. Sensors are used to capture various types of data from a building. They measure comfort-related data, such as CO_2 level, temperature, and humidity, and detect emergency situations like fires, earthquakes, and intrusions. While sensors and actuators have traditionally been connected by using wired systems, technologies such as Zigbee and Bluetooth LE have been developed to support wireless communication with general peripheral devices, including sensors and actuators [140].

To manage and control building energy, protocols for communication between sensors, actuators, controllers, energy management systems (EMS), and BEMS are necessary. Efforts have been made to establish standards for building automation protocols, including IEEEs 802.15.4, 1901, 1905.1, 802.21, 802.11ac, and 802.3at standards [141–146]. Protocols based on these open standards include interoperability among various vendors, devices, and software. However, some vendors use proprietary protocols that limit the usage of their devices and software. This has led to significant fragmentation, a frequently discussed issue in the IoT and building automation fields. Nevertheless, several open standard protocols, such as LonWorks, DeviceNet, BACnet, C-Bus, m-bus, Modbus, and KNX, are widely adopted [124].

4.4. Key Technologies for Grid Connectivity

With buildings and the power grid becoming interconnected, focusing solely on internal building communication technologies is no longer sufficient. Communication technologies that facilitate interaction between building-side and grid-side resources are now essential. To ensure stability, reliability, and efficiency, building data resources must be capable of two-way communication with the grid to exchange data and/or information. To this end, efforts are being made to develop and standardize bi-directional communication technologies and protocols related to AMI, grid code, protocols, and security between buildings and the grid.

AMI is a digital metering system that collects real-time consumption data from buildings to enable two-way communication between buildings and the grid. AMI measures building power consumption and responses, enabling accurate billing and providing grid operators with data to develop operational strategies [147].

With interoperability between buildings and the grid becoming increasingly important, various global standardization bodies are striving to standardize data protocols. The IEEE P2030 project aims to support the effective integration of building systems and devices within the smart grid by developing guidelines for the interoperability of energy technology and information technology operations with electrical systems and end-use applications and loads. Additionally, the Organization for the Advancement of Structured Information Standards and the International Electrotechnical Commission (IEC) defined standards for smart grid and user interfaces for demand response programs in 2021. Existing AMI communication standards include ANSI C12.22, ANSI C12.18, and ANSI C12.19 [124,148–150]. EEBUS strives to develop a communication interface that allows BMS-related devices to connect with each other and interact with grid and market operators, aiming to be standardized in IEC 63380-3, CENELEC EN 5063, and VDE-AR-E 2829-6-4 for grid interaction [151–154].

4.5. Key Technologies for Local-Smart Technologies

Local-smart technologies primarily focus on managing and optimizing energy consumption within buildings and leveraging advanced technologies such as real-time sensors and predictive analytics. Local-smart systems operate with limited dynamic interaction with external entities, such as the power grid. They typically rely on traditional EMS that forecast energy loads and generation based on internal data, such as historical energy usage patterns and local weather conditions. Decisions within a local-smart system, such as those related to energy management and cost optimization, are often made based on pre-established pricing schemes like Time-of-Use (ToU) tariffs. This means that the primary focus remains on optimizing the building's internal operations without extensive consideration of real-time grid conditions.

BEMS and BAS forecasting involve predicting future energy demands and environmental conditions based on historical data, real-time sensor information, and external data such as weather forecasts. The primary goal of forecasting is to optimize energy consumption, reduce operational costs, and ensure occupant comfort by anticipating changes and adjusting systems proactively [155,156]. Scheduling in the context of BEMS and BAS refers to the strategic planning and timing of operations involving building systems, such as HVAC, lighting, and appliances, to optimize energy use while maintaining occupant comfort. Effective scheduling reduces peak demand charges, lowers energy costs, and ensures the efficient operation of building systems [19,157]. BEMS and BAS pertain to the real-time management and control of building systems to ensure optimal performance and energy efficiency. This involves continuous monitoring of the system status, adjusting parameters based on occupancy and environmental conditions, and integrating renewable energy sources to maintain a comfortable indoor environment [158,159].

Maintenance within the context of BEMS and BAS encompasses strategies to ensure that building systems function efficiently and reliably. Predictive maintenance, powered by AI, involves using data analytics to anticipate equipment failures and schedule maintenance activities before any issues arise, reducing downtime and extending equipment life [160]. Specifically, AI algorithms optimize system performance and detect anomalies to enable predictive maintenance, thereby improving energy efficiency and occupant comfort [161].

4.6. Key Technologies for Grid-Smart Technologies

Grid-smart technologies are a more advanced and flexible approach to building energy management, where the building's operations are closely integrated with the power grid. Grid-smart systems actively respond to the complexities of the electricity market, participating in activities such as day-ahead energy trading, providing ancillary services, and engaging in demand-side management in real-time markets. This approach allows buildings to not only optimize their own energy efficiency but also to contribute to the stability and efficiency of the wider energy grid. Grid-smart systems may operate independently or as part of larger community energy services, such as Virtual Power Plants (VPPs) or Community Aggregation Services (CAS), ensuring that the building's energy usage is dynamically aligned with grid conditions and market signals.

Grid-smart technologies emphasize the integration and coordination of DERs across a broader electrical grid, involving collaboration between distribution system operators (DSOs) and transmission system operators (TSOs). Greater interoperability between DSOs and TSOs allows for better utilization of DERs in the system, increasing system flexibility while reducing the cost of grid reinforcement. An important factor is the behavior of the distribution link DER capacity between the buyers driving the real-time market. TSO-DSO joint optimization is vital to optimize flexibility requirements, coordinate planning, and reduce network investment costs [162].

Forecasting using AI enables a more intelligent response to changes in the grid. AI forecasting systems can integrate data from internal factors, such as renewable energy generation capabilities and flexible internal loads, as well as external factors, including weather conditions, grid status, and CO_2 levels. Utilizing AI enables optimal control of building systems, enhancing efficiency and grid responsiveness.

4.7. Key Technologies for Load Flexibility

Traditionally, building flexibility has focused primarily on reducing the energy consumption of buildings themselves. Conventional methods included passive approaches such as improving the building envelope, switching to LED lighting, or using high-efficiency HVAC systems [163]. The advent of advanced building management systems like BAS and BEMS has enabled more dynamic and systemic load adjustments to become feasible. Technologies for load shedding and load shifting not only save energy but also enhance occupant satisfaction. Recently, DERs such as photovoltaic systems and ESS have been introduced to reduce electricity consumption and manage peak loads. However, these distributed generators are primarily attended to minimize building costs. Even with the introduction of a demand response intended to alleviate grid burden, the primary focus has remained on the financial benefits for the building itself.

4.8. Key Technologies for Grid Flexibility

With grid stability becoming increasingly important, conventional building flexibility can now contribute to grid security. The U.S. DoE has identified five forms of demand flexibility, efficiency, load shedding, load shifting, modulating, and generation that can enhance grid security, many of which have traditionally served the building's own benefit [39]. Grid flexibility encompasses more than the ability of individual buildings to adjust to fluctuations in renewable energy sources, such as PV and changes in load. It involves the strategic integration of buildings with the broader energy grid. This integration aims to enhance the stability and efficiency of the grid by leveraging connections with regional renewable energy resources. Unlike internal flexibility, which focuses on optimizing energy use and load management within a single building, grid flexibility seeks to reduce overall variability and improve grid resilience through coordinated interaction with external energy sources. By leveraging grid information and through co-optimization, buildings can now help secure the grid and meet the needs of TSOs and DSOs. These approaches have primarily been driven by price signals and customer participation.

Recently, market participation in the electricity sector, once available only to the traditional players, such as utility providers, has become accessible due to flexible resources. Beyond passive methods like demand response for reducing electricity consumption, buildings can now participate in various energy and ancillary service markets through the generation of electricity from both non-dispatchable renewable energy sources and dispatchable resources such as ESS and emergency generators [163,164].

5. Discussions

Over the past few decades, various concepts and models have been proposed to improve building management. These efforts have led to the emergence of multiple building types, including IBs, GBs, SBs, and ZEBs, each emphasizing different aspects of sustainability, efficiency, and automation. To achieve the specific objectives of these building models, new technologies such as automation systems, sensor networks, advanced algorithms, and innovative facilities have been introduced.

As power systems become increasingly complex and electricity demand continues to rise, the need for enhanced power system reliability has become more critical. This has driven a growing demand for flexibility within the power grid, leading to the proposal of GEBs, which prioritize securing flexibility to improve grid stability. While traditional building models have contributed to grid stability through mechanisms such as DR, GEBs are fundamentally designed with the primary objective of providing the necessary flexibility for the power grid.

The results indicate that while GEBs share common elements with conventional models, such as efficiency, communication, and operational algorithms, they are unique in their emphasis on interaction with external systems, particularly the electrical grid, leveraging buildings as flexible resources to support grid stability. This interaction involves delegating control of the building's energy management to external authorities, such as TSOs or DSOs. Since these authorities often have their own objectives, it is crucial to establish clear agreements with building occupants and owners to ensure user convenience is maintained. Defining settlement methods between external authorities and building occupants or owners is essential for ensuring compliance and mutual benefit. For the TSOs or DSOs, the development of decision-making principles, such as determining the prioritization of resources, control of flexibility, and the allocation of resources among different controllers (TSO/DSO), is crucial. Additionally, the design of control structures and mechanisms for flexibility, the introduction of local or global flexibility markets, and the optimization of architecture among TSOs, DSOs, and other stakeholders are also areas that should be considered.

From another perspective, GEBs can differ in terms of who the subject is. This would be based on the recognition that there are limitations in utilizing demand-side flexibility with the traditional building-based approach. It can be interpreted as an effort to strengthen cooperation between power grid operators and building operators to overcome the limitations.

6. Conclusions

This study provided a comprehensive examination of GEBs within the broader landscape of existing building energy management models. We identified and emphasized the distinct characteristics of GEBs, setting them apart from other established concepts such as intelligent buildings, smart buildings, green buildings, and zero-energy buildings. Through an extensive review of literature published between 2019 and 2023, this study offers an overview and comparison of trends related to GEBs, focusing on four key features: efficiency, connectivity, intelligence, and flexibility. To deepen the understanding of GEBs, we refined and expanded the key attributes from four to eight core characteristics, revealing the unique role that GEBs play in the evolution of building energy management. This analysis highlights GEBs' distinctive emphasis on grid interactivity and dynamic energy efficiency, underscoring their potential to transform the way buildings contribute to and interact with the electrical grid.

Our findings revealed that GEBs prioritize interaction with external grids, providing flexibility and distinguishing them from conventional buildings that primarily focus on internal comfort and automation. As renewable energy sources become more widespread, the role of buildings in securing grid flexibility is expected to grow, increasing interest in GEBs.

Recent research reflects the complexity of coordinated operations between grid and building operators. Despite these complexities, GEBs offer an intuitive and effective approach to making buildings responsive to grid resources. Given the integration of energy management in various traditional building management models, GEBs are well-positioned to play a critical role in future energy systems, with expectations for their role continuing to rise as the demand for grid flexibility increases.

Future research can focus on several critical areas to advance GEBs. Enhancements are needed in probabilistic forecasting for renewable energy, adaptive demand forecasting, and the optimization of control strategies for dynamic grid interactions. The development of a bi-level optimization model could facilitate the better integration of grid systems and building energy management. Additionally, tackling contemporary challenges related to demand flexibility, load shedding, and load shifting is essential for optimizing energy consumption and improving grid stability. Pursuing these research priorities is crucial for enhancing the effectiveness, resilience, and overall performance of GEBs.

Author Contributions: Conceptualization, S.-Y.S.; methodology, S.-Y.S.; validation, S.-Y.S. and S.B.K.; formal analysis, A.B., Y.S.P., S.B.K. and S.-Y.S.; data curation, A.B. and Y.S.P.; writing—original draft preparation, A.B. and Y.S.P.; writing—review and editing, S.-Y.S.; visualization, A.B.; supervision, S.-Y.S.; project administration, S.-Y.S.; funding acquisition, S.-Y.S. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the MSIT (Ministry of Science and ICT), Republic of Korea, under the ITRC (Information Technology Research Center) support program (RS-2023-00259004) supervised by the IITP (Institute for Information & Communications Technology Planning & Evaluation) and by the Ministry of Trade, Industry and Energy, under the STEP (Strategy for Transition to next generation Energy Portfolio) support program (No. 20214000000060) supervised by the KETEP (Korea Institute of Energy Technology Evaluation and Planning).

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

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