Reducing Building Performance Through Energy-Savings Techniques

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Abstract:

Energy Management Systems in Buildings (EMS-in-Bs) are vital for optimizing energy efficiency and management. This paper reviews various EMS-in-Bs designs, focusing on their capabilities in monitoring, estimating, and controlling energy usage. It reveals that systems focused on control and optimization achieve the highest energy savings, up to 30%, compared to estimation and prediction functions, which save around 10%. The study underscores the need for advancements in estimation and prediction to enhance efficacy. Additionally, it explores Fuzzy Cognitive Maps (FCMs), a soft computing technique integrating neural networks and fuzzy logic, in building automation. FCMs have shown promising results across sectors, including medicine, transportation, manufacturing, agriculture, the food industry, and energy. This paper presents simulation and experimental results from case studies in Southern Greece, demonstrating the application of FCMs in residential and commercial buildings. Moreover, it discusses software tools based on these applications, with plans for further integration to generate real-world data. This data is crucial for advancing future research aimed at transitioning buildings from high energy consumption to achieving Net-Zero Energy Buildings (NZEB). Insights from reviewed studies guide the ongoing development of EMS-in-Bs, addressing current challenges and future directions. Buildings account for approximately 40% of global energy consumption, driving significant interest in improving their energy efficiency. The paper critically reviews traditional and modern approaches to building automation, focusing on strategies that drive energy savings. By providing a comprehensive evaluation of function-specific EMS-in-Bs, this study serves as a resource for selecting systems best suited to specific energy management needs. It highlights that control-optimize EMSs-in-Bs deliver an average energy savings rate of 22.57%, while estimate-predict systems achieve 10%, emphasizing the importance of continuous innovation in this field.

Keywords:

Energy efficiency, building insulation, Energy-efficient windows, HVAC system optimization, Smart thermostats, Energy management systems, LED lighting, Solar panels, Passive design, High-performance building materials, Building automation systems, Energy-efficient appliances, Sustainable building design, Net-zero energy buildings.

I. Introduction:

Due to political and environmental demands, energy efficiency is essential for global energy strategies, providing both economic and competitive advantages. Albania has implemented a number of programs to improve energy efficiency, with the goal of reducing overall usage by 22.5% by 2015. Thermal insulation and energy management need to be improved in commercial and residential buildings, which consume a lot of energy. To achieve energy intelligence and optimize energy savings in these buildings, advanced technologies such as alternative energy sources and energy management systems (EMS) are crucial [1]. Global energy demand has surged due to climate change exacerbated by urbanization, industrialization, and higher living standards. Fossil fuel combustion, a primary energy source, emits significant greenhouse gases like carbon dioxide, driving the need for energy-efficient building practices. Buildings require extensive resources throughout their lifecycle, making efficiency vital for reducing emissions and environmental impact. Key strategies include developing policies, improving efficiency, conducting life cycle analyses, and adopting renewable energy, all focused on boosting sustainability and cutting pollution and costs [2]. The building sector accounts for over 39% of global energy consumption, which has increased due to population expansion and technological improvements. This has resulted in a notable increase in carbon emissions. The goal of the move to almost zero energy buildings is to reduce emissions, especially in high-demand areas like China, which has the highest levels of harmful emissions worldwide, mostly from construction. In order to fight climate change, countries are enacting laws to lower emissions and encourage energy-efficient and sustainable building techniques, despite obstacles including cost, technology, and material availability [3]. In the building industry, lowering energy costs has become crucial due to the growing significance of sustainable energy management. Conventional approaches emphasize better building design, renewable energy systems, and high-efficiency appliances, but they sometimes come with hefty price tags and ignore system synergies. Efficiency can be increased by employing sophisticated strategies like data analytics, energy forecasting, and moving demand to times when costs are lower. This study presents a methodology that uses machine learning to estimate demand while integrating IoT with existing equipment (such as HVAC and CHP). It has been tested in Greece and Ireland to determine its regional efficacy [4]. Global energy consumption is rising, with buildings accounting for 34% of energy use and 37% of CO_2 emissions in 2022, emphasizing the environmental impact of the construction sector. Retrofitting existing buildings offers substantial energy-saving potential, particularly through improved building envelopes that reduce heat loss. This paper evaluates the effectiveness, cost, and sustainability of advanced materials—like phase change materials, aerogels, and vacuum insulation panels—used for retrofitting. It highlights challenges and applications across climates, aiming to aid architects and engineers in adopting energy-efficient practices [5]. To improve building energy efficiency, a variety of lighting systems (LSs) have been developed, with solutions specific to different building types yielding varying energy savings. For example, combining daylight and intelligent lighting can greatly reduce energy use while enhancing indoor comfort. Building energy management systems give LSs priority in order to increase energy efficiency (BEE) because they are significant energy consumers. It has been demonstrated that intelligent and adaptable lighting designs, including LED with alternate thermal systems and optical fiber for daylight, can lower energy use in a variety of contexts [6]. Technology has always been essential to the advancement of society and is developing at a never-before-seen rate, permeating our homes and workplaces. The idea of intelligent buildings has drawn a lot of attention during the last 20 years. The European Intelligent Building Group (EIBG) defines an intelligent building as one that minimizes operating costs by effectively managing resources and providing optimal occupant support. The final section of this study presents the findings from an investigation into Intelligent Buildings, Building Energy Management Systems (BEMS), and the comparison of conventional and fuzzy control approaches for HVAC [7]. Building lighting has a big impact on energy use, especially as it affects other systems like HVAC. Building Energy Efficiency (BEE) is enhanced by a variety of lighting systems (LSs) solutions, such as occupant profiles, timers, and daylight integration. For higher savings, large-scale or rural buildings are more suited for efficient LSs like daylighting or light management. In order to determine the best use of energy-saving LSs, this review examines both artificial and daylight systems in residential, business, and rural settings. It also emphasizes upcoming developments in energy-saving lighting solutions and the contribution of ICT to the advancement of energy-efficient LSs [8]. Energy-saving techniques are essential for increasing efficiency because of the growing demand for energy in buildings. Buildings, particularly small commercial ones, use a lot of energy, and their requirements vary depending on their age, type, and design. In order to provide insights across different building types, the BE3S assessment looks at four main energy-saving techniques: lighting systems, retrofit designs, occupant behavior analytics, and monitoring systems. BE3S seeks to direct researchers, designers, and politicians toward efficient energy-saving techniques catered to particular building contexts by examining a large body of literature from five major publishers [9]. To reduce CO_2 emissions, the Kyoto Protocol encourages renewable energy development and energy-demand reduction without compromising service quality. In 2016, Italy's electricity was largely fossil-fuel-powered, with renewables making up 37.5% of production. Key energy-saving methods include modernizing industrial equipment, adopting electric transport, and improving building systems for air conditioning and lighting. Italian shopping malls, many of which use outdated fluorescent lighting, offer high potential for energy-efficient retrofitting. This study examines a DIY store's transition to LED lighting and automation for enhanced efficiency and CO_2 reduction [10]. Building Management Systems (BMS) and Building Energy Management Systems (BEMS) are essential for optimizing energy efficiency by managing mechanical and electrical systems within buildings. BMS primarily controls HVAC, CCTV, and security systems, while BEMS focuses on energy savings, occupant comfort, and efficiency. Intelligent BEMS (iBEMS) use sensors and IoT to enhance functions like monitoring, control, and prediction. This review classifies diverse BEMS designs applied across building types, highlighting designs that balance energy efficiency and comfort, aiming to provide state-of-the-art insights into EMS functions and scopes [11].

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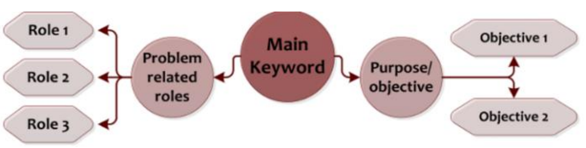
II. Literature Survey

S.no	Title of the paper	Year	Remarks
1	Reducing Energy in Buildings by Using Energy Management Systems and Alternative Energy-saving Systems	2011	Energy efficiency is crucial in Albania's energy policy, especially in commercial and residential buildings that consume significant energy. Improving building design, thermal performance, and adopting energy management systems enhances efficiency and sustainability.
2	Improving environmental performance of building through increased energy efficiency: A review	2011	Mitigation policies include regulatory (e.g., legislation, emissions controls) and voluntary (e.g., education, energy audits) measures. Energy efficiency via lifecycle analysis, low-energy materials, and passive design improves building sustainability cost-effectively.
3	A review on zero energy buildings – Pros and cons.	2021	Zero-energy structures aim to minimize energy use and boost efficiency. Key challenges include policy gaps, cost concerns, and public awareness. Enhanced incentives and research are essential for progress.
4	Smart buildings with legacy equipment: A case study on energy savings and cost reduction through an IoT platform in Ireland and Greece	2024	This paper explores reducing energy costs in buildings with legacy equipment through an IoT platform and ML algorithms for energy prediction. Demonstrations in Ireland and Greece show promising reductions in peak consumption and cost, enhancing tenant energy management.
5	Energy Retrofitting Using Advanced Building Envelope Materials for Sustainable Housing: A review	2024	This study reviews advanced building envelope materials like PCMs, aerogels, VIPs, and HRCs for residential retrofitting. It highlights their benefits for energy savings, CO_2 reduction, occupant comfort, and economic feasibility, alongside challenges in costs and installation.
6	Lighting Systems Designed for Energy Savings in Buildings (LSD-ESB): a review	2020	This paper reviews 20 years of research on energy-saving lighting control systems, highlighting effective applications across building types. While some systems are cost-effective, others, like lighting retrofits, may not be suitable for large or historical buildings.
7	New Advanced Technology Methods for Energy Efficiency of Buildings.	2020	This paper reviews energy management and comfort control systems in intelligent buildings, highlighting fuzzy logic and neural network hybrids. Fuzzy Cognitive Maps (FCMs) are recommended for efficient, direct control, enhancing energy savings and reducing control process runtime.
8	A Review: Buildings Energy Savings - Lighting Systems Performance	2020	This review highlights energy-efficient lighting systems (LSs) for diverse buildings, evaluating performance, suitability for specific settings, and energy-saving potential. It addresses current LS challenges and suggests future directions for enhancing smart, adaptable, energy-saving lighting solutions.
9	A Review on Building Energy Savings Strategies and Systems (BE3S).	2019	The BE3S paper reviews recent studies on energy-saving strategies in buildings, covering lighting control, retrofitting, occupant behavior, and monitoring systems. Each strategy's effectiveness varies by building type, highlighting the importance of scenario-specific selection for optimal savings.
10	Energy savings for indoor lighting in a shopping mall: A case of study.	2018	Replacing fluorescent lamps with LED lighting in an 8600 m^2 mall yields significant energy savings (290 MWh/year) and CO_2 reductions (97.8 t/year). Adding a BAS further cuts energy use (75.9 MWh/year) with short payback periods (4.11 and 3.49 years).
11	Energy Management Systems and Strategies in Buildings Sector: A Scoping Review	2021	This paper reviews Building Energy Management Systems (BEMSs) over 40 years, identifying monitoring, prediction, and control-focused designs. It highlights key insights, challenges, future directions, and energy-saving impacts, suggesting enhancements to estimation and prediction-oriented BEMSs.

III. Research Gap Analysis:

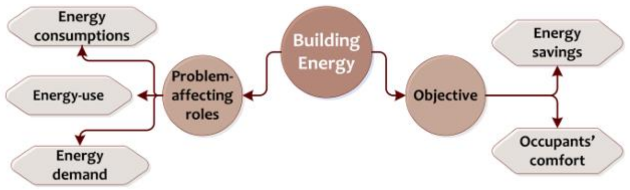
A. Problem Definition

The primary predefined term (energy building savings in the BE3S report) is impacted by a few different aspects. Energy savings may be possible once these responsibilities and elements are effectively addressed. To determine the best or semi-optimal rate of energy savings, numerous energy control techniques have been developed. Different energy savings have been attained despite the fact that different solutions have been used and deployed in diverse settings. Numerous factors influence the suggested system's ability to save a significant amount of energy in this situation. To provide a clearer picture, this is shown in Fig. 1. This study examines various suggested systems that are implemented on a variety of building types utilizing various methodologies.



B. Problem Statement-derived Keywords Selection

To effectively select keywords, the first step is to define a primary keyword seed. This core keyword should align with the main research objective, with additional related aspects clarified accordingly. For this study, the primary keyword selected is "building energy," centered around addressing a specific problem. This problem may entail multiple objectives and various factors influencing the performance of proposed solutions.



The paper's primary aim is to review systems addressing the problem statement: "building energy savings control strategies/systems." In this context, the main objectives identified are "energy savings" and "occupant comfort." Several factors play essential roles in determining the performance of energy-saving control systems, directly or indirectly impacting the achievement of optimal energy savings levels. Key factors include "energy consumption," "energy use," and "energy demand," each of which can counteract energy savings goals.

Considering these terms— "energy consumption," "energy use," "energy demand," "energy savings," and "occupant comfort"—two potential scenarios emerge, as shown in Table I. Consequently, BE3S aims to review studies proposing control systems that can achieve scenarios similar to those in Table II, with a high level of effectiveness. There exists a challenge to achieve such a scenario that is shown in Table II.

Table I

If		Then			
Factor/Role	=	Objective 1	=	Objective 2	=
energy consumptions, energy-use, and energy demand	high	energy savings	low	occupants' comfort	high
energy consumptions, energy-use, and energy demand	low	energy savings	high	occupants' comfort	low

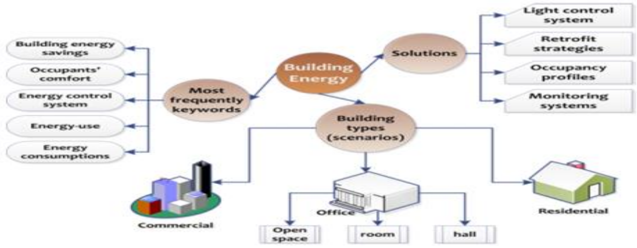
If		Then			
Factor/Role	=	Objective 1	=	Objective 2	=
energy consumptions, energy-use, and energy demand	low	energy savings	high	occupants' comfort	high

Table II

In order to accomplish a similar scenario as listed in Table II with a high degree of performance, BE3S focuses on reviewing papers that offer control systems.

C. Strategy of Keywords Generation & Selection

A straightforward keyword generation strategy has been employed. The central keyword is inherently linked to and influenced by several factors. In this approach, three primary elements are considered: the main keyword, influencing factors (or roles), and objectives, all of which are carefully accounted for. To achieve specific objectives, various solutions are implemented. These solutions are then integrated into the framework. Furthermore, solutions are applied across different building types (or scenarios), with outcomes varying based on both the designed solution and the type of building where the solution (or proposed system) is implemented. In summary, the core components consist of: the main keyword, sub-keywords (comprising influencing factors and objectives), solutions (proposed systems or strategies), and the building types where solutions are applied. This structure is visually represented in Fig. 3.



IV. ENERGY SAVINGS IN COMMERCIAL AND RESIDENTIAL BUILDINGS

The energy consumption of residential and commercial buildings depends not only on the efficiency of individual devices, like pumps, motors, fans, heaters, chillers, and lighting fixtures, but also on how these elements are integrated into systems. System-level design offers significant energy-saving potential, often far greater than device-level improvements alone, and frequently at a lower net investment. An energy-efficient building requires a collaborative design process from the start, engaging all members of the design team in an iterative selection of engineering systems and performance components. Key design choices that substantially impact a building's energy efficiency include building orientation, shape, and thermal mass; thermal performance of the building envelope; passive heating, cooling, ventilation, and daylighting strategies; selection of energy-efficient devices; and the integration of engineering systems within an energy management system (EMS) designed for energy efficiency. These strategies can often yield 35–50% energy savings for new buildings. Thoughtful design—like optimizing the building's form and envelope—can enhance daylighting and reduce heating and cooling loads, leading to smaller and more efficient mechanical systems. Though high-performance envelopes and efficient equipment may have a higher upfront cost, these can be offset by the energy savings they provide. Architects must consider the building's orientation, self-shading features, window-to-wall ratios, insulation levels, and passive ventilation and cooling opportunities, all of which contribute to minimizing energy demand from the beginning. Passive ventilation plays a crucial role in reducing mechanical energy requirements by releasing warm indoor air when cooler outdoor air is available. This approach broadens the acceptable temperature range and provides a cooling effect from air movement. It also improves air quality and offers occupants a connection to fresh outdoor air. Another effective technique, earth-pipe cooling, can pre-cool incoming air by directing it through an underground duct, leveraging the ground's naturally cooler temperature in regions with significant seasonal variations.

Boilers and furnaces remain common in residential and commercial buildings, circulating steam or hot water for heating. Boiler efficiencies generally range from 80–95%, and modern furnaces achieve similar rates, from 78–96%, although distribution losses are not included. Newer systems offer substantial savings compared to older models, which often operate at just 60–70% efficiency. Wall-mounted boilers are particularly efficient, reaching over 90% efficiency for domestic hot water and space heating needs. Heat pumps, which transfer heat indoors in winter and outdoors in summer, measure efficiency using the coefficient of performance (COP). By drawing heat from sources like the ground or exhaust air and distributing it at low temperatures (as in radiant floors or ceilings), the system minimizes temperature lift and maximizes COP.HVAC systems provide heating, cooling, and ventilation. In traditional setups, a fixed air volume is circulated to maintain the desired temperature, often exceeding ventilation needs. Modifications, such as variable-air-volume systems with adjustable-speed fans, heat exchangers for exhaust air recovery, and demand-controlled ventilation, can cut energy use significantly. EMS systems that adapt indoor temperatures seasonally based on outdoor conditions also improve efficiency. Hydronic systems, using water instead of air for heating and cooling, are generally more energy-efficient than forced-air systems and reduce infiltration. They allow temperatures closer to the setpoint, improving efficiency and comfort. Lighting also presents considerable energy-saving potential through efficient lighting systems, daylighting, and zone controls. Retrofit projects often yield 30–50% savings in electricity, while deep daylighting strategies can save up to 90% in certain spaces. Collectively, these strategies show that energy-efficient design in all building types and climates can achieve 50–75% or more in energy savings over typical local building practices, underscoring the vast potential for energy efficiency.

V. BUILDING ENERGY MANAGEMENT SYSTEM (BEMS)

The Building Energy Management System (BEMS) plays a crucial role within the larger Building Automation System (BAS), essential for controlling and optimizing building operations. Given the high energy demands of heating, cooling, and domestic hot water production, there is an emphasis on designing systems that can effectively manage these areas to minimize energy consumption. In recent years, the complexity and sophistication of mechanical and electrical systems in buildings have increased significantly, making BAS ideal for integrating various building subsystems, including lighting, fire alarms, and HVAC systems. This allows for streamlined monitoring, control, and management of complex functions within modern structures emphasized that BAS serves as an efficient and effective control tool for building management, we also noted that BAS can control HVAC systems to yield substantial energy and cost savings.

BAS unifies multiple subsystems to enhance insight into building performance through energy measurement, optimized system strategies, and improved, building automation encompasses the computerized monitoring, control, and management of building services, with building control forming a key component of overall building automation. Since the oil crisis of the 1970s, the focus on energy-saving measures has underscored the role of automation in energy management. Particularly for BEMS, controlling active systems like HVAC has become central to reducing both energy consumption and operational costs.

1. HVAC Systems: An Overview

As an active subsystem of BAS, HVAC systems have a major impact on energy use, making it essential to understand their operation and structure. We can also note that energy efficiency and indoor climate control are fundamental considerations in HVAC system design. A typical HVAC system comprises several subsystems, including the indoor air loop, refrigerant loop, chilled water loop, condenser water loop, and outdoor air. Each loop involves multiple dynamic variables, resulting in a nonlinear, time-variable system subject to disturbances and uncertainties.

Due to the complex, variable nature of HVAC systems, developing an accurate mathematical model and designing an appropriate controller is challenging. HVAC systems account for approximately 50% of a building's total energy consumption, underscoring the potential energy savings achievable with robust controller design.

2. Retrofit Design for Energy Savings

When compared to new buildings, this is one of the preferred applicable solutions for existing buildings in particular since it helps save energy in a shorter amount of time while preserving the buildings' structures. On the other hand, building retrofitting is sometimes seen to be expensive and ineffective for short- and medium-term use. As a result, suggested systems trying to create such techniques face a number of difficulties. In this context, the main goal of such a retrofitting system is to suggest a plan for converting a traditional building into a smart one. However, a wide range of alternative transformation and retrofit scenarios are taken into account. For instance, a proposed study that was assessed took into account a number of criteria and aspects, such as energy efficiency, optimizing energy fluxes, and smart grid interactivity.

3. Occupants Profiles for Energy Saving

It has been noted that certain systems and tactics centered on energy conservation attain a high degree of energy-use efficiency. The comfort of the inhabitants, however, may not always be given much thought [55]. Therefore, it is necessary to consider both energy savings and occupant comfort. Certain energy-saving systems and strategies are highly efficient in reducing energy use, yet they may not fully account for occupant comfort. As a result, both energy savings and occupant comfort must be balanced. To develop systems that achieve this, researchers have examined space characteristics and occupant behavior patterns to inform energy system parameters. With a lighting retrofit applied to replace the existing fluorescent system, the proposed setup has successfully reduced energy consumption by 43% compared to the previous lighting system. An interesting simulation study was conducted on a residential home in Lithuania, aiming to explore the relationship between energy consumption and occupant behavior.

4.Commercial vs. Residential Building Occupants' Influences on Energy Demand:

Numerous research studies and systems have been developed to explore the relationship between occupant behavior and energy demand. Findings have varied widely across different building types, even with identical input parameters. For example occupant behaviors and characteristics have a significant impact on energy demand, particularly in residential buildings. In contrast, occupants have only a minor influence on energy consumption, noting that energy demand can remain high even when occupancy is reduced. However, it acknowledged that by adjusting for occupancy patterns, substantial energy savings can be achieved.

Highlighted age, behavior, and the number of occupants as the most influential factors in occupancy profiles affecting energy use and demand. To reconcile these differing perspectives, it is suggested that in commercial or non-residential buildings, such as academic facilities, occupant-profile-based energy control systems may be less effective and not achieve optimal energy saving. Alternative strategies could be more effective in these settings. On the other hand, occupancy-based control systems are well-suited for residential buildings when factors such as occupant age and behavior are considered.

VI. CONCLUSION

The BE3S review paper synthesizes research from the past two decades across several renowned databases, including IEEE, Elsevier, Emerald, MDPI, and ACM, all indexed by Scopus or WOS. It focuses on various strategies aimed at enhancing building energy savings. Specifically, the review categorizes these strategies into four major types: lighting control systems, retrofit design systems, occupant profile and behavior-based systems, and monitoring systems. The impact of each strategy on energy conservation varies based on the type of building it is applied to. For instance, a particular strategy might yield substantial energy savings for one building type but may not perform as effectively for another. The paper notes that lighting control systems are particularly beneficial in commercial spaces where occupant profiles and behaviors are individually accounted for. Time-scheduled lighting control systems are well-suited for academic buildings, such as universities, as they align with specific academic periods. Retrofit strategies, meanwhile, offer high energy-saving potential when applied to newly constructed buildings. Occupancy-based strategies, however, may be less effective in office settings that account for subgroup behaviors, but they can be highly effective in residential buildings by considering occupant behavior, activities, and age. Monitoring systems are best suited for smart buildings equipped with sensors, which can also reduce costs in smart city applications. The review emphasizes the importance of considering various factors to identify the most effective energy-saving systems for specific building scenarios.

Additionally, the paper explores control systems that contribute to energy management and occupant comfort in buildings. It highlights that intelligent buildings aim to maximize both comfort and energy efficiency, making control strategies essential to achieving this balance. Various control systems are assessed for their strengths and weaknesses in managing building parameters. The analysis suggests that advanced control systems, particularly those using hybrid methods like fuzzy logic and neural networks, can significantly improve building energy efficiency. Combining fuzzy logic and neural networks in control systems offers the advantage of leveraging both techniques' robust characteristics while minimizing their individual limitations. Fuzzy cognitive maps (FCMs), due to their straightforward mathematical modeling and adaptability, are recommended for direct control in building automation systems. FCMs allow for a reduced control process runtime and, with their inherent learning capabilities, can help decrease energy consumption. Given the global energy crisis and the finite nature of energy resources, achieving greater energy savings through building automation systems has become critical. FCMs, as direct control systems, support these energy-saving goals by reducing runtime and energy use.

The paper also highlights the importance of energy efficiency in global energy policy, a focus that is expected to continue due to environmental and climate concerns. In Albania, energy efficiency is integrated into government strategies and action plans. Buildings in Albania play a significant role in the country's energy efficiency potential, with commercial and residential buildings consuming nearly 40% of primary energy and approximately 77% of electricity. The energy consumption of buildings largely depends on the integration of various energy-using systems rather than the efficiency of individual devices. By enhancing the thermal performance of building envelopes, selecting optimal building orientations and thermal masses, implementing passive heating, cooling, and ventilation solutions, and carefully choosing energy-efficient devices, commercial and residential buildings can reduce their energy consumption substantially.

However, achieving energy efficiency goes beyond just using passive techniques or improving individual energy devices. True energy efficiency aligns with a broader concept of energy intelligence, which involves maximizing the utility of primary energy consumed. This approach integrates effective energy-saving strategies with user convenience and long-term cost savings. In this context, the implementation of Energy Management Systems (EMS) in both commercial and residential buildings is essential for achieving energy efficiency goals and ensuring reliable building infrastructure operations.

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