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Research Article

Innovative Techniques for Enhancing Building Energy Efficiency: A Comprehensive Review

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ABSTRACT

This review paper provides a literature review on the state of the art, recent development of energy efficiency for smart building with findings published in the past five years. And it shows how growing Building Energy Efficiency (BEE) and decreasing energy usage innovative approaches and technologies are being used. Common methods for assessing and forecasting energy utilization are presented, and methods for adapting the internal configuration of a building to supply energy efficient performance are addressed. Particular emphasis is placed on the control of luminaires because their efficiency greatly determines energy consumption. The review looks at diverse energy conserving strategies such as the energy application forecasts, IoT facilities in smart buildings, innovations in light management systems and employing of quad code services informing occupants of energy consumption rates. Further, the emulation of various methods of retrofitting interior designs is also discussed with a focus on the aspect of energy efficiency. This paper also discusses the effectiveness of applying these methods under different circumstances, given particularity of the building design or operation, and environmental contexts. Based on a synthesis of data from the latest studies, this review provides recommendations for implementing energy-efficient solutions following specific construction requirements. The result provides an addition on the existing knowledge regarding the implementation of sustainable building practices in conforming with worldwide energy standard. By so doing the paper highlights the importance of technological inventions and design techniques which contributes to the paper's purpose of being a useful tool for researchers, architects, and policymakers in the provision of energy-efficient buildings in the future.

1. INTRODUCTION

Building Energy Efficiency or (BEE) has attracted much interest in the last few years because of its importance in energy informatics and the sustainability ladder. These 2 approaches drawn more academic researchers and governmental organisations to look for new approaches and solutions to improve BEE to reduce unexpected energy consumptions and the impacts on the environment. The overall aim of these efforts is to curtail energy consumption in buildings, which account for between a third and a half of total global energy consumption as well as contribute significantly to CO_2 emissions [1].

Although, efforts have been made and conceptualised for developing techniques and strategies for enhancing BEE. These comprise methods of forecasting energy use, measurement, and new methods of efficient energy design. Another area that has been identified as a main focus in improving energy efficiency is contained in remodeling of building interiors and specifically, effective manipulation of illumination systems. Nonetheless, the problems persisting in the measurement of BEE, the prediction of energy consumption, and the technical and cost barriers to retrofitting and complex control systems are to be also cited.

This paper provides a comprehensive review of recent advancements in BEE techniques, focusing on three critical aspects: BEE measurement and energy-use prediction, lighting control systems and internal layouts retrofit. These areas mentioned in the review are the areas of development and the progress has been made in these areas such as predictive methods to energy usage that have shown a high level of accuracy and efficiency. However, issues like high cost associated with some of retrofitting solutions and demands of the technological solutions that can be replicated more easily are also discussed.

To enhance the currency and richness of this review, the paper focuses on articles that have been published within the last five years with additional information derived from earlier seminal works. Some of the topics covered are 'energy use in

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buildings', 'intelligent buildings' 'IoT solutions', 'lighting management systems', and 'energy consumption predictability'. The combination of these two approaches offers readers an insight into the present status of BEE techniques and limitations, and allows them to decide on a case-by-case basis which strategies are best suited for the application to particular buildings. It is hoped that this review will prove useful to the researcher, practitioner and policymaker by providing an overview of the current state of the art for upgrading energy efficiency in buildings using advanced methods and technologies. In this way, the paper contributes the closer examination of both the positive factors associated with BEE, as well ahs the issues that currently present significant challenges, toward the ongoing improvement of the constructed built environments as sustainable systems of energy delivery.

2. RELATED WORK

Building Energy Efficiency (BEE) is a field that has drawn much attention in the last decade with scholars proposing methods of reducing energy use while preserving the functions of buildings and the comfort of the users. It presents summaries of the breakthroughs and methods described in the recent research, which gives a base for the comprehension of the current issues in the field.

Measurement and prediction of energy consumption in buildings are the core activities to energy efficiency. Many past works like those in [2, 3], have used data-based techniques including machine learning to forecast energy consumption with high levels of accuracy. Some of the AUTCs comprehensively employed forecasting methodologies include regression analysis technique, artificial neural networks, and ensemble learning techniques for energy-use pattern forecasting. In addition, with the help of smart meters and IoT sensors, the degree of detail in the collected energy data has improved, thus allowing the real-time tracking and regulation of the building's energy systems [4, 5]. Still, there are several challenges that are related to the integration of the mentioned technologies and infrastructures because of the compatibility problems and high cost of implementation.

Interior lighting can be identified to account for a high proportion of the total energy use within building structures. For instance, various scholars have presented sophisticated lighting control solutions that have considered energy efficiency. For example [6], showed that motion-sensor-based systems and automated daylight harvesting make the building energy efficient. in the same manner, the intelligent solutions for IoT-based lighting are discussed in [7] which provides for the control and scheduling of the complete lighting systems to mainly conserve energy. Although such systems have been found to provide high reliability, they are still limited from real implementation by challenges like high initial costs and requiring expert in house personnel to manage and maintain the systems.

New investigation about residential buildings reveals that building upgrades is becoming a significant way to develop BEE especially in the area of thermal improvement, ventilation and lighting. As in [8, 9] Retrofitting has been discovered to play a pivotal role in lowering the energy consumption especially in older building designs. In addition, new interior arrangement techniques that involve efficient use of energy in construction and deployment of efficient interior designs also state that this aspect increases energy performance without compromising on the appearance. However as pointed out by [10], retrofitting activities have constraints like cost, time frame for implementation and constraints by the building being used for retrofitting project.

The adoption of IoT technology in the management of the smart building has brought in a new frontier by keeping record of energy usage and then improving their management. Studies in [11, 12] also focus on the use of IoT in the automation of some electrical devices such as energy, HVAC and lightning. Other forms of systems based on QR codes have also been proposed in [13] with the purpose of offering notifications to occupants on energy use, which enhances energy responsible behavior. Nevertheless, modern trends are still concerned with such problems as data protection, system's capacity, and interaction between different systems.

Some comparative research has been conducted to compare the effectiveness of diverse BEE techniques under diverse building categorizations. For example, [14] offers comparison of predictive models, lighting control systems, and retrofitting measures, as well as their strengths and weaknesses. Numerous techniques indicate high promise, significant issues on scale-up, cost, and technical hurdles ongoing curtail their applicability in the actual world.

Collectively, this review gives an understanding of the strengths and limitations of different BEE techniques featured in such and other studies. In achieving the above objective, this paper hopes to plug the current research gaps and direct subsequent research and development endeavours towards more effective and energy-efficient building processes. Please refer to table I which summarises the main conclusions and issues specific to each characteristic of BEE.

TABLE I: SUMMARY AND ANALYSIS OF RELATED WORKS IN BUILDING ENERGY EFFICIENCY

Aspect	Key Findings	Challenges
BEE Measurement and Energy-Use Prediction	Data-driven techniques (e.g., machine learning, IoT sensors) improve energy-use prediction accuracy.	High implementation costs, compatibility issues with existing systems.
Lighting Control Systems	Motion-sensor-based systems, daylight harvesting, and IoT-enabled solutions significantly reduce lighting energy consumption.	Initial setup costs, need for skilled maintenance personnel.
Retrofitting and Interior Design Enhancements	Retrofitting improves thermal insulation, ventilation, and lighting in older buildings, enhancing overall energy efficiency.	High project costs, long timelines, building-specific constraints.

Smart Building Technologies and IoT Integration	IoT enables real-time energy management for HVAC, lighting, and occupant behavior monitoring; QR codes encourage energy-conscious behavior.	Data security concerns, scalability issues, and lack of interoperability across systems.
Comparative Studies	Highlights advantages and limitations of various techniques like predictive models, retrofitting, and smart systems.	Scalability, cost, and technical complexity limit widespread adoption.

3. METHODOLOGY

3.1 Introduction to the Applied Strategy

This paper specifically discusses Building Energy Efficiency (BEE) as well as research on energy usage with an emphasis on newly developed literatures. The literature review section explains the procedure adopted in the analysis of studies that advance new measures on regulating and managing the energy usage of structures. Most of the reviewed articles belong to the articles published in the period between 2016-2021; however, several vital historical articles and studies were also incorporated into the analysis, extending up to the last decade. That approach makes it possible to obtain not only the information on the latest advances in the subject but also the historical past of the discipline's advancements.

3.2 Research on BEE Measurement Techniques

This section looks at the methods which have been suggested in the literature for assessing BEE. One of the most important studies [14] formulate a five-step methodology that includes data gathering, data pre-processing, data normalization, clustering, and BEE estimation. Cleaning up the data included handling errors in data (e.g. containing some missing or cut off values because of network connection) and applying normalization to the energy-use data set for each chronological period. Normalization was performed using Equation (1):

$$Normalized\ Energy\ Use = \frac{Energy\ Use\ at\ Time\ Interval\ i}{Maximum\ Energy\ Use\ in\ Day\ d}$$

As shown in Figure 1, the methodology involves multiple steps, beginning with data preprocessing and normalization.

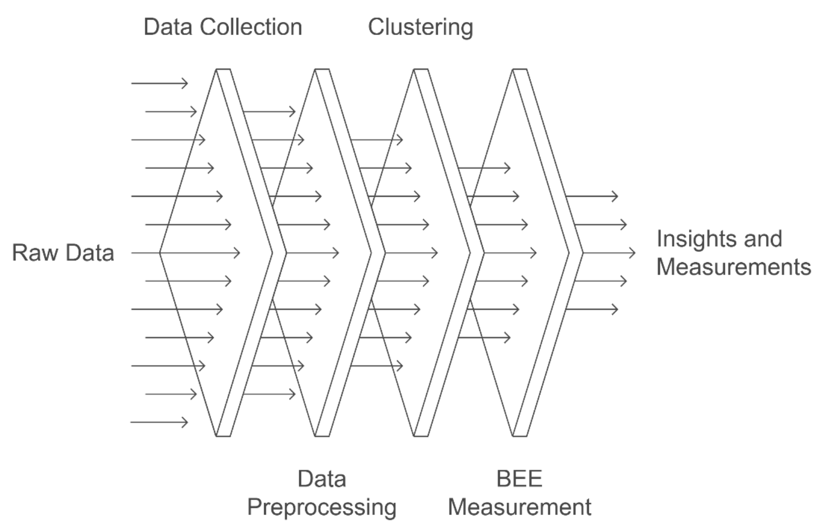

Fig 1: Flowchart of BEE Measurement Process.

Data was then aggregated into WD and NWD and sub segmented by working and non-working hours. With threshold-based clustering by Euclidean distances, energy use was categorized into high-medium-low groups. This classification allowed for the computation of the BEE score defined as the proportion of energy used outside working hours to total energy used at all hours. On the other hand, lower values corresponded to higher energy efficiency of the buildings. These techniques did confirm efficient energy-use predictions especially in differentiating between work-related and non-work usage. In the working hours, the power peaks, and the power lows are compressed in a similar manner as shown in figure 2 in order to determine the energy-use density.

Fig 2: Data Clustering for Energy-Use Patterns

3.3 Energy-Use Predictability and Evaluation Methods

Models predicting energy-use have emerged as popular in the recent past. In [16], energy-use predictions were based on occupant profiles under different conditions (working/non-working hours for instance). Another study [17] suggested constant energy profile monitoring at half an hour interval to detect changes due to occupants. This method of data collection required the measurement of consumption figures at fixed times over a prescribed period, determining the daily mean energy consumption and the effect that various actions and conditions, including temperature changes, put on this figure. Other important findings pointed that energy consumption during business hours hovered at 35 kW – 58 kW depending on the extent of heat and lighting requirements. Hence, the present assessment emphasizes the role of occupant behavior for modeling and enhancing energy performance. For instance, Figure 3 illustrates that energy use differs sharply between working and non-working periods.

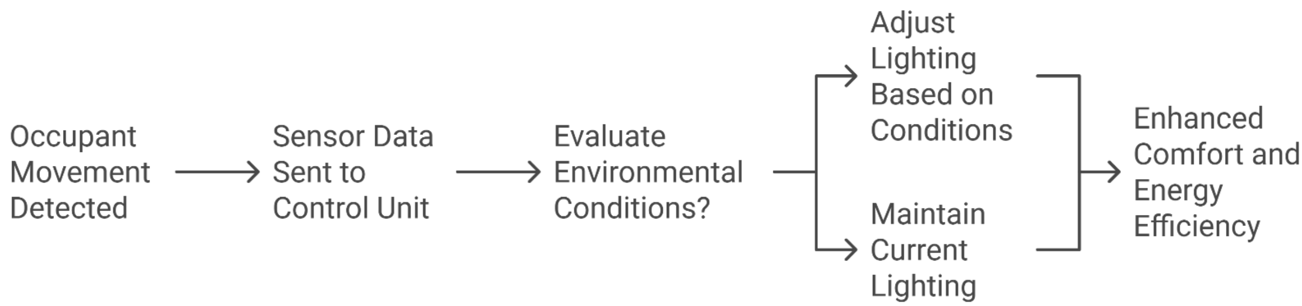

Fig 3: Energy-Use Profiles for Working vs. Non-Working Hours

3.4 Innovative Interior Design Techniques for Energy Efficiency

This section provides a synchronised canvass of strategies toward enhancing energy utilisation by transformative interior designs of commerce buildings. Writing in [18], the authors explored illuminance control systems which alter L with reference to the dynamic occupancy and environmental conditions within a given T. These systems guaranteed control of energy and at the same time achieved comfort of the occupants.

Another approach [19] employed multiple criteria decision-making tools in order to develop interior environment energy performance. This method involved gathering information about the occupant behavior and energy consumption in order to develop the decision-making plan. The process consisted of two phases: decision design and decision implementation constitute two main stages in the study of decision making. In the first phase of the conduct, it assessed building characteristics including building energy use and indoor and outdoor environment to come up with a retrofit strategy. The second phase generated enhanced solutions based on conditions in specific buildings and included suggestions for improvements on energy systems such as HVAC. This approach showed considerable promise to decrease energy consumption significantly through integrating retrofit interventions according to the functionalities and physical properties of standalone structures. Figure 4 below illustrates the decision-making tool used to define retrofit strategies with high energy efficiency.

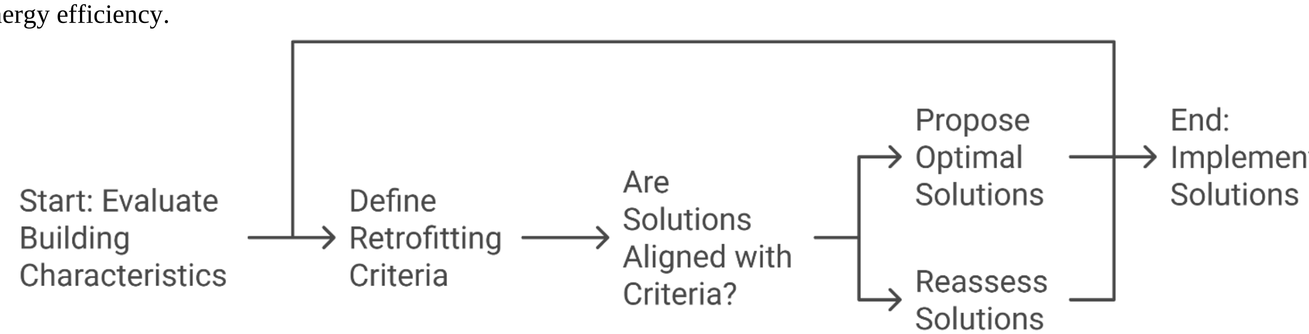

Fig 4: Multi-Criteria Decision-Making Framework for Retrofitting

3.5 Integration of Retrofitting and Connected Grids

In cases of buildings connected to grid, further optimization has been put forward in [20]. These comprised retrofitting interventions for more than one building, taking into account the architectural and physical environment, structural, and technical requirements. We specifically forwarded several plans that embraced the inter-building cooperation in order to get the maximum BEE. Honestly, retrofitting measures entailed improving the equipment, installing incorporating energy-efficient designs and other measures that ended in a positive improved performance of the grid. Such methodologies put forward a standard practice of energy efficiently which was easily adaptable for every building type and atmospheric conditions. The retrofitting plan that examines how efficiency can be enhanced in connected grids is shown in Fig. 5.

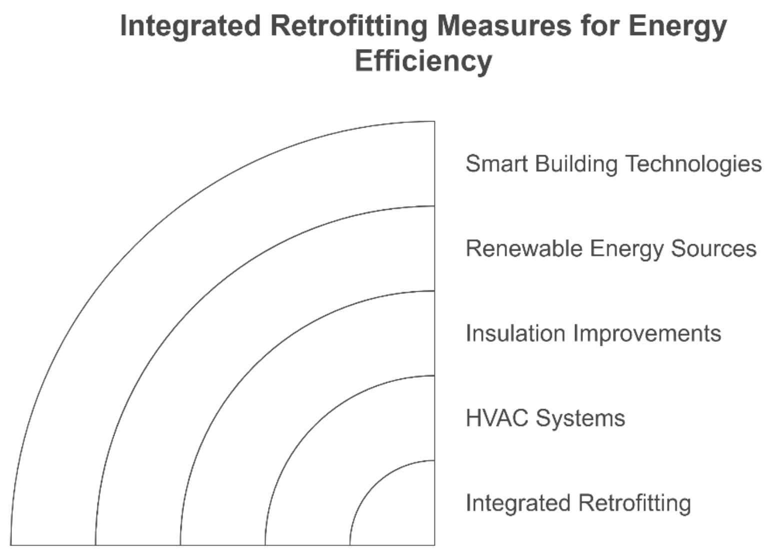

Fig 5: Retrofitting Plan for Connected Grids.

4. ANALYSIS OF BEE TECHNIQUES

This section presents an evaluation of approaches suggested for implementation towards BEE so that their effectiveness, drawbacks, and enhancements are described. Of all the methods that have been tested here, some have well-proven the methods of measurement and energy use reduction; others have had difficulties such as depending on certain building conditions, the extent of engineering complications, and fees of implementing energy-conserving methods. The procedure of this paper is divided into sub-sections with regards to elements of BEE techniques.

4.1 BEE Measurement

The effectiveness and efficiency of BEE measurement techniques could therefore depend on aspects such as the design and age of the construction, the compatibility of its technology with BEE techniques among others. It is clear from [21] that integrating contemporary sensor systems into existing structures and infrastructures for real estate remains a struggle because of construction complexities and compatability. These challenges culminate into higher installation costs together with lower energy efficiency. On the other hand, contemporary constructions incorporate connected features and precursor outlets for place sensors, which are less costly and highly effective.

Different research works have looked at ways of managing energy use through special forms of light control systems. Light settings including the use of preference-based light settings [22, 23] and deep learning approaches such as neural network algorithms [24] can assist to control the illuminance levels ‘enhancing energy saving. Nonetheless, other occupant activities result to high energy usage that affects the BEE performance. In response to these challenges, one research [25] developed a semi-automated system that would design near optimal BEE solutions for retrofitting existing buildings with minimal implementation issues. Therefore, figure 6 compares the installation difficulties in sensors of the older buildings with that of the modern buildings. The know-how confirms the problems related to structures: the high installation costs and the complexity of connectivity in the case of the older buildings, compared to the possibilities of easy installation, low costs and reliable connectivity of the modern premise.

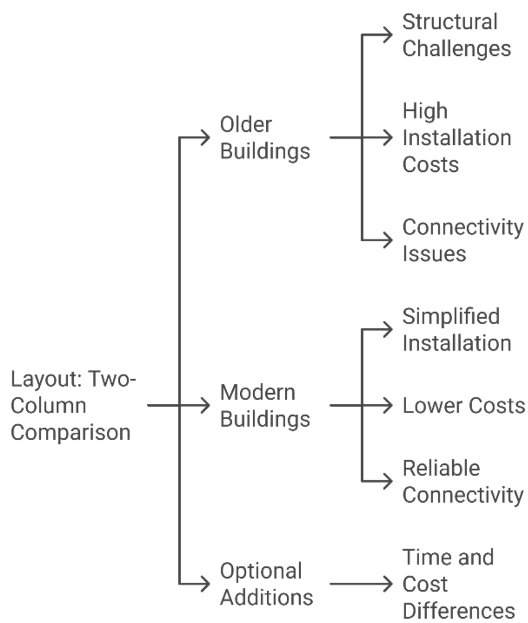

Fig 6: Comparison of BEE Measurement Challenges in Older and Modern Buildings.

4.2 Entropy-Based BEE Predictability

To improve the forecast of dynamic energy-use behaviour, entropy-based techniques have been introduced. For instance, using Figure 7, [26] revealed a strong relationship between entropy values of between 0.4 and 0.8 with high energy-use times of in the day typically associated with lower non-working hours both for WD and NWD. Such findings imply that entropy analysis can aptly capture key energy peaks to help in designing ways of enhancing BEE.

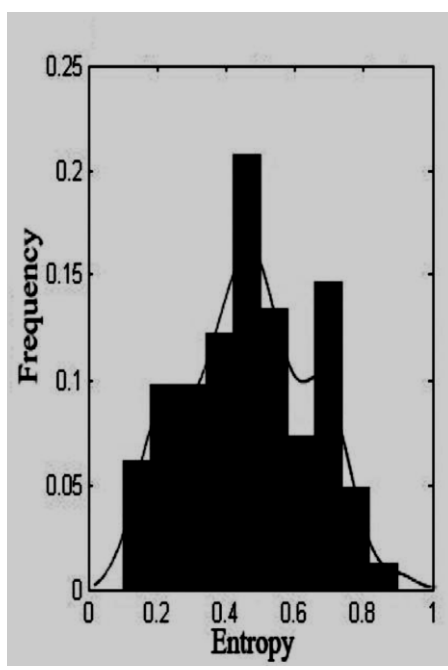

Fig 7: Predictability of BEE based on entropy distribution

4.3 Energy-Use Optimization

There are many MCDM tools designed for improving energy efficiency by relating some aspects such as energy usage rate, cost with construction, and CO_2 emission [19, 20]. These tools assist in the design of affordable systems for the minimization of energy consumption. Other works have future concentrated on environmental effects [21–23] , characteristics of the building, and the use of sustainable energy savings. For example, there are strategies for retrofitting [24,25] and optimization of portfolios of connected buildings, [26,27] that can decrease energy consumption. However, problems like high costs and restricted possibilities do not permit them to achieve a high level of performance.

4.4 IoT and QR-Code-Based Solutions

In recent years, the use of IoT based systems for smart building has come into practice due to a potential that allows real time data and control on energy management. The authors of one [29] developed an IoT device, an experimental refrigerator and utilized it to monitor and estimate energy efficiency with residents of the building. Although issues regarding the smart plugins and data availability, the system successfully promoted the energy saving attitudes by reporting data from one user to another and monitoring specific sectors. QR-code techniques have also been used to improve IoT systems as well as other IoT enhancements. For instance, Advanced Metering Infrastructure (AMI) opens opportunities for QR codes to read the data concerning energy usage, inform inhabitants, and calculate costs in real time [30, 31]. AMI was introduced in figure 8 regarding to an envisaged application in a smart building environment where it is pinned on capability to enhance the aspect of energy awareness.

Fig 8: AMI is the calculation of energy cost and the real-time notification of inhabitants [31].

4.5 Comparative Analysis of Techniques

Table II provides a summary of the advantages and disadvantages of various BEE techniques. Each method offers unique strengths, such as low-cost designs or adaptive systems, but also faces challenges like implementation complexity, cost, or limited applicability.

TABLE II: COMPARATIVE ANALYSIS OF BEE TECHNIQUES

Ref.	Study Purpose	Advantages	Disadvantages
[10]	Energy-use and BEE measurement in residential buildings	Low-cost design compared to retrofitting interior designs	Limited testing across diverse building designs
[8]	Light control system design	Adaptive illuminance control	Complex hardware systems (e.g., sensors)
[9]	Occupant profile-based decision-making	Effective portfolios for connected buildings	High costs
[12]	Behavior-based BEE measurement	Improved predictability of dynamic energy-use behavior	Fixed parameters, internet connectivity issues
[29]	IoT for smart buildings	Interactive user engagement for energy efficiency	Challenges with smart plugins and data availability

5. CONCLUSION

In this paper, all the latest and most innovative methods of improving Building Energy Efficiency are described with focus on the advances, issues and solutions seen in the existing research. The results emphasize the importance of using advanced technologies in climate control, incorporating the IoT system, intelligent lighting control, and entropy of energy consumption for future prediction. New construction environments offer the convenience of incorporating smart technologies into building structures and relatively cheaper retrofit integrations unlike existing environments, most especially those with old architectures, whereby BEE techniques encounter some structural and technological barriers. Techniques like, modifying the interior design of a building, energy control according to preference, presence of an automated decision-making system, have shown great potentiality in saving energy of a building but cost factor, scalability factor and behavioral factor are the challenges that need to be solved. Combining IoT services such as AMI as well as QR-code applications has been identified as a viable mechanism for monitoring smart building utility usage in real-time and with optimization. However, connectivity problems, as well as non-unified systems throughout the applications of these technologies, remain to be the primary concerns up to this date. It also emphasizes unique and context-specific assessment tools for assessing the effects of renovations on the environment and the costs and energy savings of using multi-criteria decision instruments valid for different building types. By dealing with these challenges, future research can unveil more potential integration of machine learning, IoT, and advanced control system that can improve BEE further. This research is a helpful source of information for researchers, practitioners, and policymakers to identify the best approaches and their drawbacks to help meet energy sustainability in the built environment worldwide. The continuous enhancement of SBEI solutions and basic technologies focused on scale, cost, and integration continues to be crucial for broad implementation of energy efficiency improvements in the building stock.

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Conflicts of Interest:

The authors have no conflicts of interest to disclose.

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