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Energy Efficient Buildings in the Industry 4.0 Era: A Review

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Abstract: The fourth industrial revolution has resulted in the digitalization of projects and operations across all sectors. Accordingly, efforts are being made to utilize advanced technologies to improve the energy efficiency of the building sector. This study has reviewed the current application and limitations of cutting-edge technologies in this regard. An overview of the use of the Internet of Things (IoT), artificial intelligence (AI), digital twin (DT), and building information modeling (BIM) for energy efficiency of buildings has been provided. It has been found that the use of Industry 4.0 technologies, during the construction and operational phase of buildings, has a great potential to reduce energy consumption and emissions of the sector. This study may help stakeholders of the built environment to understand the role of industry 4.0 tools for energy efficiency of the sector.

Keywords: Internet of Things; artificial intelligence; digital twin; building information modeling; industry 4.0

I. Introduction

It is projected that the frequency of extreme weather events, due to climate change, will be enhanced with time [1]. The building sector, due to its huge energy consumption and emissions, is considered at the forefront of the campaign for sustainable development [2,3]. According to the reports, the building sector accounts for 40 % of total energy consumption and 36 % of carbon emissions [4]. Efforts are being made, across the globe to take initiatives for lowering energy consumption in the building sector, and most of the countries have already set their action plans in this regard [5]. Countries are making huge investments in establishing the infrastructure for energy efficiency, and extensive rebates are also conferred by governments to individuals and organizations who are adopting measures for energy efficiency. The energy efficiency appeal is widely accepted owing to its potential not only for saving in utility costs but also for reduction in emissions.

With the advent of Industry 4.0, cutting-edge technologies can play a contributory role in reducing the energy consumption of the building sector [1]. It has been reported that the integration of innovative technologies in building operations has the potential to reduce energy consumption by up to 14 % percent in retail stores and 18 % in offices [6]. During recent years, there has been a proliferation of research studies undertaken on the integration of industry 4.0 tools for the energy efficiency of buildings. However, most studies have focused on a specific technology for the energy efficiency of buildings, and there is a need to provide an overview of the current use of these technologies and their limitations in one study. By reviewing the literature on the subject, this study aims to provide insights into this domain.

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II. Building Energy Efficiency in Industry 4.0 Era

The use of building automation systems has emerged since 1980 [7]. Initially, automation systems were decentralized and were used to control different functions of buildings separately [8]. However, with time, the capacity of automation systems has enhanced, and now a single system can monitor and control different functions of a building [7]. The enhanced capability of automation systems, with the advent of Industry 4.0 and the availability of robust technologies, can help greatly in promoting the energy efficiency of the built environment [9]. Several technologies, including the Internet of Things, (IoT), artificial intelligence (AI), digital twin (DT), and building information modeling (BIM), are being integrated with building systems to improve energy efficiency. The following sections will provide an overview of the application of these technologies for energy efficiency in buildings.

A. Building Energy Efficiency through IoT

The advent of IoT offers interesting opportunities for its integration across all sectors [10]. While interconnecting several devices through data collection and sharing, IoT provides an automation system for the buildings which can be controlled by the building owner through a smart device easily [11]. The IoT has led to the formulation of the Internet of Energy (IOE), which utilizes the IOT in distributed energy systems for improving energy efficiency and resultantly reduces the detrimental effects on the environment [12].

Researchers have worked on the integration of IOT for buildings' energy efficiency, Khan, et al. [13], in a study utilizing Android Smartphones and FLIROne, collected 50 thermal images and identified insulation problems of the building with an accuracy of 75 %. These thermal images were taken from outside and inside of the building to identify the temperature difference. In another study, Metallidou, et al. [12] proposed a template for smart buildings to improve energy efficiency. They utilized a remote-control method, which was supported by a cloud interface for improving the energy performance of existing buildings. While utilizing IoT, Humayun, et al. [14] proposed a green energy system model for the optimization of energy at both the building level and city level. The mathematical evaluation of their model suggested that this model has enormous potential to save energy in different dimensions of smart cities, which includes buildings, smart homes, street billboards, and smart parking. Similarly, Kumar, et al. [10] in their study used I0T to achieve energy efficiency through a smart construction architecture. The results of their simulation highlighted that by utilizing the Constrained Application Protocol (CoAP) method in the designed smart building, energy consumption was reduced by 30.86 %. In a similar work, Wang, et al. [15] utilized a Wi-Fi probe-based method for occupancy detection, and their method saved up to 26.4 % of energy.

It has been found that studies on IoT for building energy efficiency have mostly focused on energy markets, users, and devices, however, building design aspects have not been considered [16]. Future studies may be undertaken on the application of IoT for building energy efficiency while considering the design aspects.

B. Building Energy Efficiency through AI Techniques

Artificial intelligence can be defined as the capability of computers to undertake intelligent tasks that could not have been undertaken by machines previously [17]. Due to the surprising benefits of AI, it has been widely used across all sectors. Accordingly, AI techniques such as deep learning (DL) and machine learning (ML) have been used to develop solutions for the built environment [1]. AI utilizes predictive modeling and data analytics while getting input from historical data and past experiences to develop human-like reasoning capacities in machines [17]. This way, machines can predict and forecast future occurrences or certain events.

Several studies have been undertaken for the integration of AI in buildings to promote energy efficiency. In this regard, Le, et al. [18] proposed four AI techniques to forecast the heating load of the buildings. They concluded that out of the proposed techniques, the genetic algorithm model proved to be as most efficient for efficiently calculating the heating loads. For calculating anomalous energy consumption in buildings, DirvenData [19] proposed a model based on AI and a rule-based algorithm. This model calculated the difference between the predicted and the real energy consumption. While utilizing a multi-objective genetic algorithm (MOGA) and artificial neural network (ANN), Satrio, et al. [20] optimized the operations of the chiller system in a building. The optimization considered two objectives wherein ANN was used to perform correlation between objective functions and decision variables while MOGA provided various possible design variables. In another work, Ilbeigi, et al. [21] proposed a reliable optimization method for building energy consumption using Energy Plus software for evaluating and scrutinizing the critical factors arithmetically. They also created an ANN with a multi-layer perceptron model (MLP) for simulating energy consumption. Finally, they optimized the energy consumption of the case study building by the Galapagos plugin, which relied on a Genetic Algorithm based on the crucial variables. While proposing a Recurrent Neural Network (RNN) method for building energy consumption, Aowabin Rahman [22] compared its robustness and accuracy with the ANN method. They found that the estimation of energy consumption can be improved by the RNN method in comparison to the ANN method. While using the ML method, Shiyu Yang [23] proposed a model for a predictive control system for building automation systems and compared it with a conventional reactive control system for controlling mechanical ventilation and air conditioning in a lecture hall. Their proposed method reduced electricity consumption by 36.7 % and energy consumption by 58.5 % for air conditioning. In another work, Marijana Zekić-Sušac [5] created prediction models for the energy efficiency of a public sector building using a Rpart regression tree, Deep neural networks, and Random forest with variable reduction procedures. They concluded that the most accurate results were given by the Random forest method.

It has been found that AI-based techniques have advanced substantially. However, owing to data complexity and uncertainty in design parameters for building energy management problems, the computational cost is still high [24], and thereby, utilization of soft computing for building energy management is still limited.

C. Building Energy Efficiency through Digital Twin

The concept of DT was proposed for the first time in 2011 and was used in aircraft design. Due to its ability to replicate the real world, the concept gained popularity within no time, and DT is currently used by several industries. The use of DT can radically alter the architecture engineering and construction (AEC) sector [25]. The virtual representation of the real-world building environment through DT is aiding operators and designers to devise a control and design strategy [26]. The integration of database and sensor systems has promoted the use of DT [27].

Several studies have been conducted on the use of DT for building energy efficiency. While utilizing DT, Seo and Yun [27] proposed a framework to assess energy efficiency strategies in university buildings. They developed a DT for their case study, which was based on 9 university buildings, including 55 rooms. It was concluded that by using an infrared sensor, there is a potential to reduce power consumption by 60 %. In another study, Lydon, et al. [28] used the DT for the optimization of concrete roof structures for space conditions by geothermal renewable energy resources. While using ML approaches, Lin, et al. [29] created a hybrid DT model for capturing the building's HVAC system dynamic behavior for the occupant's satisfaction and energy efficiency. In another work, Bayer, et al. [30] proposed a method for calibration and validation of a DT for a multifunctional and prefabricated façade element for radiant heating. Similarly, using DT, Clausen, et al. [31] designed and implemented a framework for buildings to perform predictive controls while getting input from weather forecasts, planned and current occupancy, and the prevailing state of the controlled environment. They demonstrated their case study in an institutional building whereby DT controlled the heating and ventilation system. The application of this model resulted in a comfort level comparable with a commercial building management system, and the model has the potential for energy saving as well.

Despite the possible benefits of DT for the built environment, its implementation is still in its infancy, and the major impediments to the adoption of DT are the lack of available technology, the absence of standards and tools, workforce upskilling, data security, and complexity of DT technological systems [32,33]. Efforts to overcome these impediments by the concerned stakeholders may help in improving the energy efficiency of the built environment.

D. Building Energy Efficiency through BIM

BIM provides an integrated model that can be utilized for the storage and communication of geographic information, spatial and geometric relationships, properties and quantities of building components, material inventories, cost estimates, and schedules [34]. BIM is known for its potential to transform the methods for the integration of environmental and energy models within building systems [35, 36]. While opening pathways for a digitalized industry and society, BIM can improve the energy efficiency of buildings [37]. A subset of BIM, known as building energy modeling (BEM), provides the robust integration of energy analysis throughout the life cycle stages of buildings. BEM, in contrast to conventional energy simulation tools, is not only less time-consuming but also can develop complex models effectively [38]. BEM provides a range of tools throughout the building lifecycle stages for energy analysis and, therefore, helps in improving the energy performance of buildings [39].

Several researchers have utilized BIM for building energy efficiency [40] and explored the potential to embed parameters in BIM architectural model files for enhancing energy efficiency at the early design stages. They concluded that the available BIM tools have the potential to add value to the design process and can result in energy-efficient outcomes. Similarly, Di Giuda, et al. [41] utilized BIM for the maintenance and management of an existing school building based on a process and technological innovation. For the energy-efficient reuse and refurbishment of public buildings, they proposed advanced design standards and validated them on the selected building. While providing an overview of competencies and skills required for utilizing BIM for buildings' energy efficiency, Alhamami, et al. [37] highlighted that BIM can contribute a lot to buildings' energy efficiency with the provision of adapted educational programs and BIM training.

Though BEM makes energy analysis easier than conventional tools; nevertheless, there exist several interoperability issues between BIM to BEM methodologies that need to be overcome to enhance the efficiency of the process [42]. Future studies may focus on eliminating the interoperability issues between BIM to BEM methodology.

III. Conclusions

The application of Industry 4.0 technologies for building energy efficiency and their limitations have been reviewed in this study. It has been found that the available cutting-edge technologies have enormous potential for reducing the energy consumption of the building sector.

The capability of building automation systems has enhanced substantially with the use of IoT, AI, DT, and BIM. These technologies are used in combinations for monitoring and controlling several building functions. Currently, advanced technologies are used during different lifecycle phases of buildings to lower energy consumption. Nevertheless, there are still areas where integration of these technologies is faced with different challenges, and therefore, the full potential of industry 4.0 tools is yet to be realized in this regard.

Future studies may be undertaken to address the limitations as highlighted in the paper for better integration of industry 4.0 tools for improving the energy efficiency of the building sector. The overview provided in the study may help decision-makers and practitioners in knowing the role of industry 4.0 technologies for energy efficiency in the building sector.

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