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Advances in building energy management systems (BEMS): A comprehensive review with bibliometric analysis and future research directions

Very Sihombing [a], Erkata Yandri [a, b, *], Kukuh Priyo Pramono [a], Ratna Ariati [a, b]

[a] *Graduate School of Renewable Energy, Darma Persada University*
Jl. Radin Inten 2, Pondok Kelapa, East Jakarta, 13450, Indonesia

[b] *Center of Renewable Energy Studies, Darma Persada University*
Jl. Radin Inten 2, Pondok Kelapa, East Jakarta, 13450, Indonesia

Abstract

Building energy management systems (BEMS) are essential for enhancing energy efficiency and sustainability in buildings. This literature review analyzes BEMS research trends from 1982 to 2024, utilizing bibliometric analysis based on a dataset from Scopus. The study identifies key developments that influence all publications and emerging research topics in the field. While BEMS offers significant potential for real-time energy monitoring and control, challenges remain, including the need for standard protocols, improved cybersecurity, and cost-effective solutions for small buildings. This research highlights the importance of addressing these challenges to foster wider adoption of BEMS technology and contribute to a sustainable energy future. The findings aim to guide future research directions and enhance the implementation of BEMS in various building types.

Keywords: bibliometrics analysis; building energy management systems; building sustainability; energy efficiency; energy monitoring.

I. Introduction

In the face of global climate change and increasing energy demands, the need for sustainable and energy-efficient building practices has never been more critical. Buildings account for a significant portion of global energy consumption, making the quest for innovative solutions to regulate and reduce energy use paramount. Building energy management systems (BEMS) have emerged as pivotal tools in this endeavor, enabling real-time monitoring and control of various energy systems within buildings, including lighting, heating, ventilation, and cooling. By optimizing these systems [1] BEMS can significantly reduce energy consumption [2][3], operational costs [4][5], and greenhouse gas emissions [6].

Building managers may now monitor and regulate a range of energy systems in real time, including lighting, ventilation, and heating and cooling [7][8][9]. Energy use, expenses, and greenhouse gas emissions can all be lowered in this way [10]. Building energy optimization has been the main focus of the fast expansion of BEMS research in recent years.

Research on BEMS has expanded rapidly in recent years, driven by advancements in technology and a

* Corresponding Author. erkata@gmail.com (E. Yandri)

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growing awareness of the importance of energy efficiency. However, a comprehensive literature review reveals substantial gaps in the current body of knowledge. Most research has concentrated on enhancing energy efficiency in commercial buildings, often neglecting the residential sector. Furthermore, there is a notable lack of studies exploring the integration of BEMS with cutting-edge technologies such as the internet of things (IoT) and artificial intelligence (AI). Additionally, existing BEMS solutions are frequently perceived as expensive and complex, which hinders their widespread adoption, particularly in smaller buildings. O. Pendram *et al.* examined a range of optimization strategies and techniques employed for energy in buildings. The main emphasis is on multi-objective optimization (MOO) with the aim of diminishing energy consumption, expenses, and environmental repercussions [11]. A. Dahiru *et al.* conducted a study on how climate change affects energy use and how proper technologies and management practices can help us adapt and decrease its impact [12]. D. M. Hernández *et al.*, study was conducted to provide a complete overview of the many tactics and technologies that may be utilized to optimize energy management and control in buildings, as well as future research areas to improve energy efficiency [13]. However, there are substantial gaps in the BEMS research that require attention and resolution. First, the predominant area of research in BEMS is centered around enhancing energy efficiency in commercial buildings, while residential structures receive minimal consideration. Second, there are substantial gaps in BEMS research that require attention and resolution. Primarily, the predominant area of research in BEMS is centered around enhancing energy efficiency in commercial buildings, while residential structures receive minimal consideration. Furthermore, there is a lack of research on the incorporation of BEMS with other cutting-edge technologies such as the internet of things (IoT), artificial intelligence (AI), and renewable energy. Third, there is still a need to create BEMS that is more affordable and simple to use.

This study aims to assess the trends and directions of BEMS research based on bibliometric analysis of scientific publications indexed in Scopus and answer the following research questions (RQs): RQ1: What are the main trends and developments in BEMS research? RQ2. What are the most influential and widely cited publications in BEMS research? RQ3: Which countries do the most research based on the Scopus dataset? RQ4: What are the most frequently co-occurring keywords in BEMS publications? RQ5: How can BEMS improve energy efficiency and sustainability in buildings? RQ6: What are the main challenges and opportunities in research in implementing BEMS? This research will also identify the most promising BEMS research topics in the future.

This study aims to address these gaps by conducting a bibliometric analysis of BEMS research published from 1982 to 2024. By systematically reviewing the trends and developments in the field, this research seeks to identify influential publications, emerging research themes, and the geographical distribution of BEMS studies. The findings will provide valuable insights into the challenges and opportunities present in BEMS research and implementation, guiding future research directions and promoting the adoption of more effective and user-friendly BEMS solutions.

II. Materials and Methods

Bibliometric methodology is the use of quantitative approaches on data sets obtained from file-type bibliographic database files provided by Web of Science, Scopus, Dimensions, Lenses, and PubMed [14]. Several bibliometric research guidelines have been formulated by researchers some of which includes Ahmi (2021) in the book "Bibliometric Analysis for Beginners" states that bibliometric analysis involves mapping and measuring various indicators related to scientific publications such as the number of publications, the number of citations received, collaborations, author networks, and publication trends and patterns in a field of research [14]. Donthu *et al.* (2021) give an outline of bibliometric methods and detailed instructions on how to use them in business research investigations. They talk about how bibliometric analysis has become more popular recently and mention that it is because software and databases are easier to get as well as the impact of information science on other fields. They also discuss about different science mapping techniques used in bibliometric analysis, such as citation analysis, co-citation analysis, bibliographic coupling, shared word analysis, and co-author analysis [15]. Bernatović *et al.* (2022) conducted a comprehensive review on the field of hidden knowledge in management using three bibliometric techniques: document co-citation analysis, co-word analysis, and bibliographic coupling [16]. The main purpose of bibliometric analysis is to find out the extend of impact a research has in a field through publication trends, evaluate its impact based on several metrics, and visualize and map the literature based on specific network analysis [17]. Bibliometric analysis enables researchers to methodically investigate and analyze substantial amounts of scientific data, emphasizing the evolutionary intricacies of particular fields and the emergence of new areas within them [18]. This methodology also provides various techniques and procedures for conducting bibliometric analysis, assisting researchers in understanding the bibliometric and intellectual structure of a field by analyzing the social and structural relationships between various research components such as authors, countries, institutions, and topics [14][15]. Bibliometric methodologies can be employed in BEMS research to ascertain the most promising research topics, evaluate the impact of BEMS research, and forecast future trends in the field. For the research procedure with bibliometric analysis, the following is a practical guide, as shown in the flowchart in Figure 1.

This study employs bibliometric analysis to assess the trends and directions of building energy management systems (BEMS) research. Bibliometric analysis utilizes quantitative approaches to analyze scientific publications, providing insights into publication trends, citation patterns, and the overall impact of research within a specific field.

A. Data collection

BEMS stands for "building energy management system". It is a computerized control system that helps build and use energy more efficiently. BEMS can manage many energy systems, including those that heat and cool, light, airflow, and appliances. BEMS can help cut down on energy use, costs, and greenhouse gas emissions [19][20][21].

The bibliometric analysis technique used is performance analysis based on biblioMagika® and science mapping with VOSviewer, First, the number of BEMS publications per year. Second, the source of publication and the country that contributes the most to BEMS research. Third, analysis of publications that are widely referenced. Fourth, citation analysis. Fifth, bibliographic coupling analysis and visualization with iipmaps. Sixth, co-occurrence analysis.

A clear scope of BEMS research and the use of appropriate search terms are essential to ensure that the research produces accurate and insightful findings. The following are some of the search terms that can be used for BEMS research. The keywords and strategies to find relevant publications on building energy management systems (BEMS) are based on title, abstract, and keywords. The dataset for this analysis was obtained from the Scopus database, a comprehensive bibliographic database known for its robust features in bibliometric analysis. The search strategy focused on

Figure 1. The bibliometric analysis procedure [15].

publications related to "building energy management system", utilizing specific keywords in the title, abstract, and keywords fields. The inclusion criteria were limited to publications in English and final articles, while non-English publications and articles in press were excluded. Based on data coverage, Scopus was chosen as the data set for this research because Scopus has powerful bibliometric analysis features that can be used to analyze research data [17][18]. The dataset obtained from Scopus will be cleaned before proceeding. Data cleaning will involve the removal of duplicates, correction of typos, standardization of author names, and standardization of publication titles using OpenRefine [14][15]. Before analysis, the dataset underwent a cleaning process to ensure accuracy and consistency. This involved the removal of duplicate entries, correction of typographical errors, and standardization of author names and publication titles using OpenRefine. The final dataset comprised 972 documents, including journal articles, conference proceedings, book series, and reports.

B. Bibliometric settings

The bibliometric analysis was conducted using various techniques, including performance analysis. This involves assessing the number of publications and citations over time to identify trends in BEMS research from 1982 to 2024. Second, citation analysis: this technique evaluates the most cited publications, helping to identify influential works in the field. Third, bibliographic coupling analysis: this method visualizes the connections between publications based on shared references, revealing collaborative networks and research themes. Fourth, co-occurrence analysis: this analysis examines the frequency of keywords in the publications to identify prevalent research topics and emerging trends. Fifth, science mapping: utilizing software tools such as VOSviewer, the study visualizes the citation networks and keyword co-occurrences, providing a graphical representation of the research landscape in BEMS. By employing these methodologies, the study aims to provide a comprehensive overview of BEMS research, highlighting key trends, influential publications, and potential areas for future investigation.

III. Results and Discussions

The Scopus database yielded 972 documents related to building energy management systems (BEMS). As shown in Table 1, these documents originated from various sources, including journals, conference proceedings, book series, books, trade journals, and reports.

Table 1.
BEMS publication sources and totals.

Source type	Total publication
Journal	449
Conference proceeding	436
Book series	62
Book	19
Trade journal	5
Report	1

Table 2.
Summary of key bibliometric metrics in BEMS research (1902-2024).

Main information	Data
Publication years (PB)	1982 - 2024
Total publications (TP)	972
CiTable year (CY)	43
Number of contributing authors (NCA)	3,483
Number of cited papers (NCP)	774
Total citations (TC)	16,354
Citation per paper (CP)	16.83
Citation per cited paper (CCP)	21.13
Citation per year (CY)	389.38
Citation per author (CA)	4.70
Author per paper (AP)	3.58
Citation sum within h-core (CHC)	13,574
h-index (HI)	61
g-index (GI)	101
m-index (MI)	1.42

The data includes publication period, number of publications, and various metrics commonly used to measure research impact and productivity. The provided data in Table 2 offers a comprehensive overview of BEMS research from 1982 to 2024. It encompasses metrics such as publication count, citation frequency, and author contributions, which collectively shed light on the evolution and impact of BEMS research within this timeframe.

Table 2 describes the main information of the publication dataset about the BEMS word search which includes the followings. First, it shows the range of years from 1982 to 2024. Second, the total number of publications included in the dataset is 972. Thirdly, the cited years, which refers to the duration in which citations are considered, is 43 years. Third, the number of contributing authors is 3,483. Fourth, the number of articles cited by other researchers is 774. Fourth, total citations of the number of times the publication was cited by other researchers was 16,354. Fifth, the citation per article, which divides the total number of citations by the number of publications to see how often each publication is cited on average, is 16.83. Sixth, citations per cited article, which divides the total number of citations by the number of cited articles to see how often each cited article is cited on average, which is 21.13. Seventh, citations per year, which divides the total number of citations by the number of years cited to see how many citations are received per year on average. i.e. 389.38. Eighth, citations per author where divides the total number of citations by the number of contributing authors to see the average number of citations per author, which is 4.70. Ninth, authors per article, which shows the average number of contributing authors per publication, namely 3.58 authors per article. Tenth, the h-index where this metric is a way to measure the productivity and impact of the researcher's publications, which is 61. Eleventh, g-index where it takes into account the number of times the most cited article by the researcher is cited, which is 101. Twelfth, the m-index was to overcome some of the limitations of the h-index and g-index. It takes into account the number of citations the researcher's publication receives, as well as the number of publications the researcher has, which is 1.42.

A. Performance analysis

Performance analysis can show that select publications have been widely published and cited by other researchers, indicating that the said research has had a significant impact. Figure 2 shows the trend of publications and citations of BEMS publications over the research period (1982-2024). This graph provided a visual overview of the development of BEMS research over time.

Figure 2 provides an overview of the evolution of BEMS based on Scopus publication data. The trend in the number of BEMS publications increased rapidly from 1982 to 2024, especially from 2010 to 2023. The year with the highest number of BEMS publications is 2022 (90 publications). This shows that BEMS research is increasingly active and in demand. The citation trend of BEMS publications increases rapidly from 1982 to 2024. The year with the most total citations of BEMS publications is 2018 (1,661 citations). This shows that BEMS research is increasingly having a major influence on research.

Bibliometric analysis enables the identification of sources that consistently publish high-quality BEMS research. These sources play an important role in advancing the research field and disseminating knowledge to the scientific community. As shown in Figure 3.

Figure 3 shows the scientific publications published in the scaled journals Energy and Building (49), Energies (44), and Applied Energy (25). The identification of the top 20 most productive sources for BEMS publications in Figure 3 provides important insights into the key contributors to this research area. Understanding these sources can help BEMS researchers stay abreast of the latest trends, identify new research opportunities, and contribute to the advancement of the field as a whole.

Bibliometric analysis helps identify highly cited articles, which are often considered groundbreaking and influential within a specific field of research. As illustrated in Table 3, these highly cited documents represent the most impactful works related to building energy management systems (BEMS).

Table 3 shows the 10 most referenced BEMS documents. The top 10 most referenced BEMS documents were published in renowned journals, namely Renewable and Sustainable Energy Reviews, IEEE Transactions on Smart Grid, Journal of Building Engineering, Building and Environment, Energy and Buildings, Renewable and Sustainable Energy Reviews,

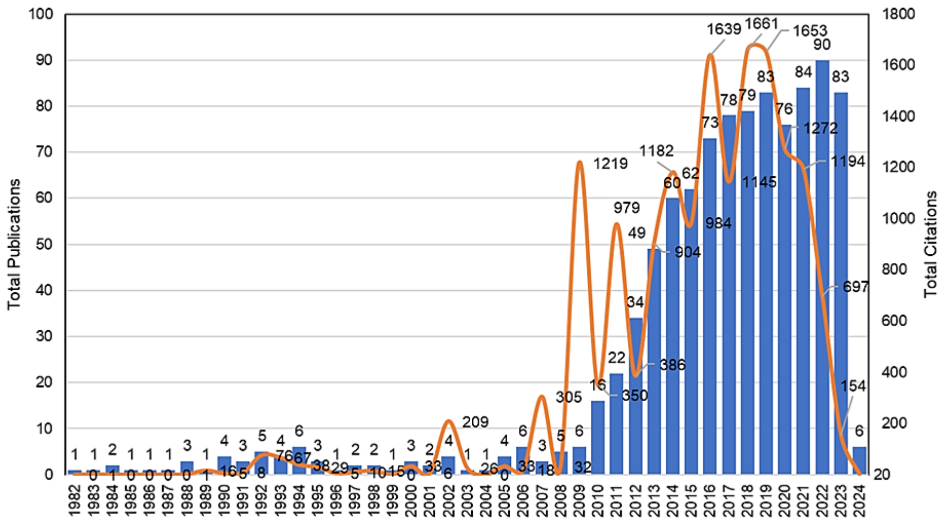

Figure 2. Annual trends in BEMS publications and citations (1982–2024).

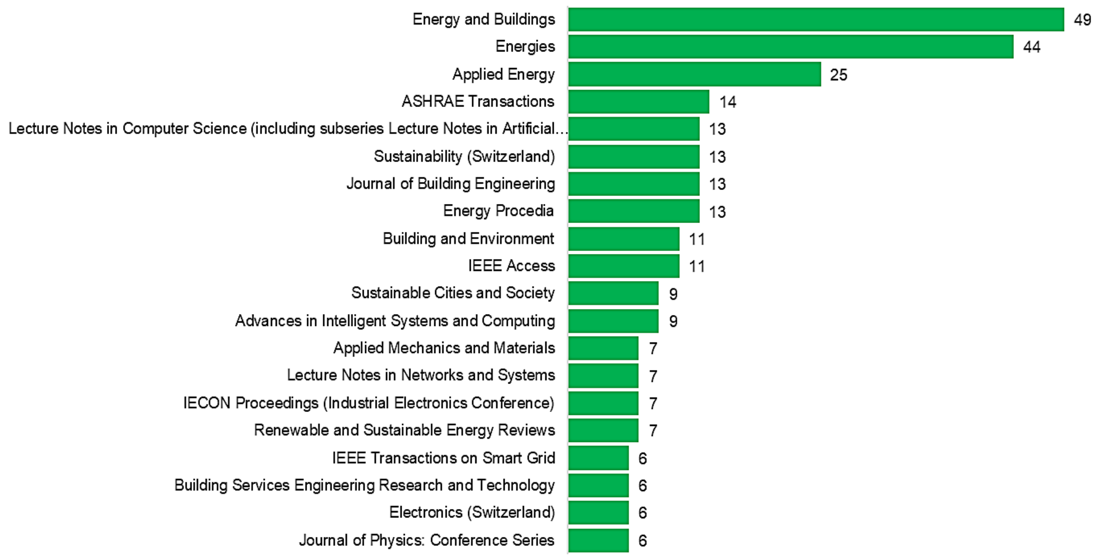

Figure 3. Top 20 most productive sources for BEMS publications.

and IEEE Transactions on Smart Grid. The first highest-referenced journal is Dounis and Caraiscos [22]. The second highest reference ranking is Du and Lu [23], who, in their research, propose an innovative algorithm for scheduling electricity loads in households. This algorithm considers cost and user convenience and can be used in household energy management systems to help residents save energy and electricity costs. The third highest reference ranking, Mocanu *et al.* [24], highlights the potential use of deep machine learning for online building energy optimization. This approach leverages data from advanced metering infrastructure to create smarter and more efficient building energy management systems. As the fourth highest reference ranking authors, Hernández *et al.* [13] highlight the importance of management strategies in BEMS systems to achieve energy efficiency in buildings. Improving building energy efficiency is important to reduce overall energy consumption. The fifth highest reference ranking, Doukas *et al.* [25], propose an innovative model that

Table 3.
Top 10 most cited publications in BEMS research.

Reference	Author(s)	Year	TC
[22]	Dounis A. I and Caraiscos C.	2009	699
[23]	Du P. and Lu N.	2011	519
[24]	Mocanu E. *et. al.*	2019	383
[13]	Mariano-Hernández D. *et. al.*	2021	285
[25]	Doukas H. *et. al.*	2007	277
[26]	Ahmad M. W. *et. al.*	2016	245
[27]	Missaoui R. *et. al.*	2014	243
[28]	Lee D. and Cheng C.	2016	236
[29]	Wang F. *et. al.*	2018	198
[30]	Zhao P. *et. al.*	2013	190

integrates with the existing BEMS system. This model can help building managers make smarter decisions regarding energy consumption and occupant comfort. The sixth highest reference ranking is of Ahmad *et al.* [26], whose research provides a comprehensive overview of available technologies for energy metering and environmental monitoring, their drivers, advantages and disadvantages, factors that influence technology selection, and future research and development directions. The seventh highest reference ranking, Missaoui *et al.* [27], provide a comprehensive overview of energy metering and environmental monitoring technologies, along with their drivers, advantages, and disadvantages. The article also discusses factors that influence technology selection and future research and development directions. The eighth highest reference ranking is Lee *et al.* [28], discusses the effectiveness of energy management systems (EMS) in saving energy. The article concludes that energy management systems can be an effective solution to save energy in various sectors, such as buildings, industries, and equipment use. The development of functions within the EMS plays an important role in improving the effectiveness of energy saving. The ninth highest reference ranking, Wang *et. al.* [29] discusses the optimization of daily operation of BEMS where they propose an innovative model for BEMS operation optimization. The model aims to achieve a balance between electricity cost savings, building occupant comfort, and the balance of different energy loads. The tenth highest reference ranking, Zhao *et. al.* [30] discusses an innovative BEMS using a multi-agent-based decision-making approach. They highlight the importance of energy optimization in buildings.

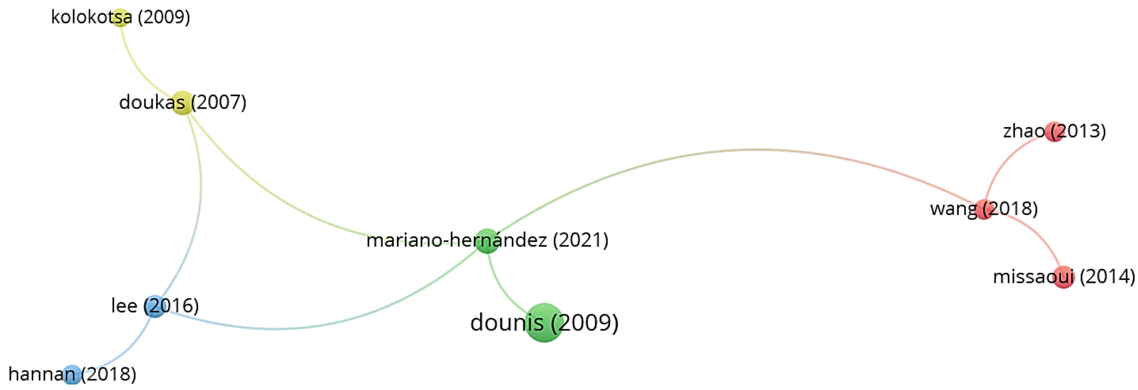

Figure 4. Visualization of the citation network in BEMS by VOSviewer.

The proposed multi-agent approach enables smarter and coordinated decision-making in the BEMS system to achieve energy efficiency and cost savings.

B. Science mapping by citation analysis

The visualization of the BEMS citation network using VOSviewer provides a valuable tool for understanding the structure and dynamics of BEMS research. By analyzing this network, researchers can gain insights into the most influential research topics, emerging trends, and potential collaborations within the BEMS research community.

Figure 4 visualizes the citation network of the 15 citation network BEMS documents, with a minimum citation threshold of 160. Table 4 further categorizes these documents into four clusters based on the citation network analysis. Cluster 1 (red) focuses on a specific research area within BEMS, while Cluster 2 (green) delves into a broader, foundational aspect of the field. Cluster 3 (blue) explores a niche topic within BEMS, and Cluster 4 (yellow) investigates a cross-disciplinary area related to BEMS.

Table 4.
Cluster themes based on citation networks analysis.

Author(s)	Reference	Citations
Cluster 1 (Red)		
Missaoui (2014)	[27]	243
Wang (2018)	[29]	198
Zhao (2013)	[30]	190
Cluster 2 (Green)		
Dounis (2009)	[22]	699
Mariano - Hernández (2021)	[13]	285
Cluster 3 (Blue)		
Hannan (2018)	[31]	186
Lee (2016)	[28]	236
Cluster 4 (Yellow)		
Kolokotsa (2009)	[32]	160
Doukas (2007)	[33]	277

In Table 4, the citation analysis of each cluster shows four main themes from each cluster in research on BEMS. First, intelligent energy management systems for homes. Second, advanced control systems are used for energy management and comfort in buildings. Third, the internet of things (IoT) is based on BEMS, and fourth, there is a rule-based intelligent building energy management system. If it is concluded based on the visualization of the citation network on BEMS and themes, the building energy management system continues to grow. This can help to improve energy efficiency and comfort in buildings by utilizing IoT and artificial intelligence (AI) based BEMS.

C. Science mapping by bibliometric coupling analysis

The bibliometric coupling analysis network visualization of BEMS research by country, as shown in Figure 5, is a valuable tool for understanding global collaborations and national contributions in this field. This network can help BEMS researchers identify potential collaboration partners, understand global research trends, and contribute to the overall advancement of BEMS research.

Figure 5 presents a visualization of the global BEMS research network, focusing on countries with at least five publications in the Scopus database. This network highlights the collaborative relationships and knowledge exchange among researchers from different countries. The United States, China, and South Korea emerge as prominent hubs in this network, with strong connections to numerous other countries. This suggests that these countries play a significant role in shaping the global BEMS research landscape.

Figure 6 provides a visual representation of the global distribution of BEMS research by iipmaps, leveraging an interactive map to showcase the number of publications from each country. This visualization offers a clear and intuitive understanding of the

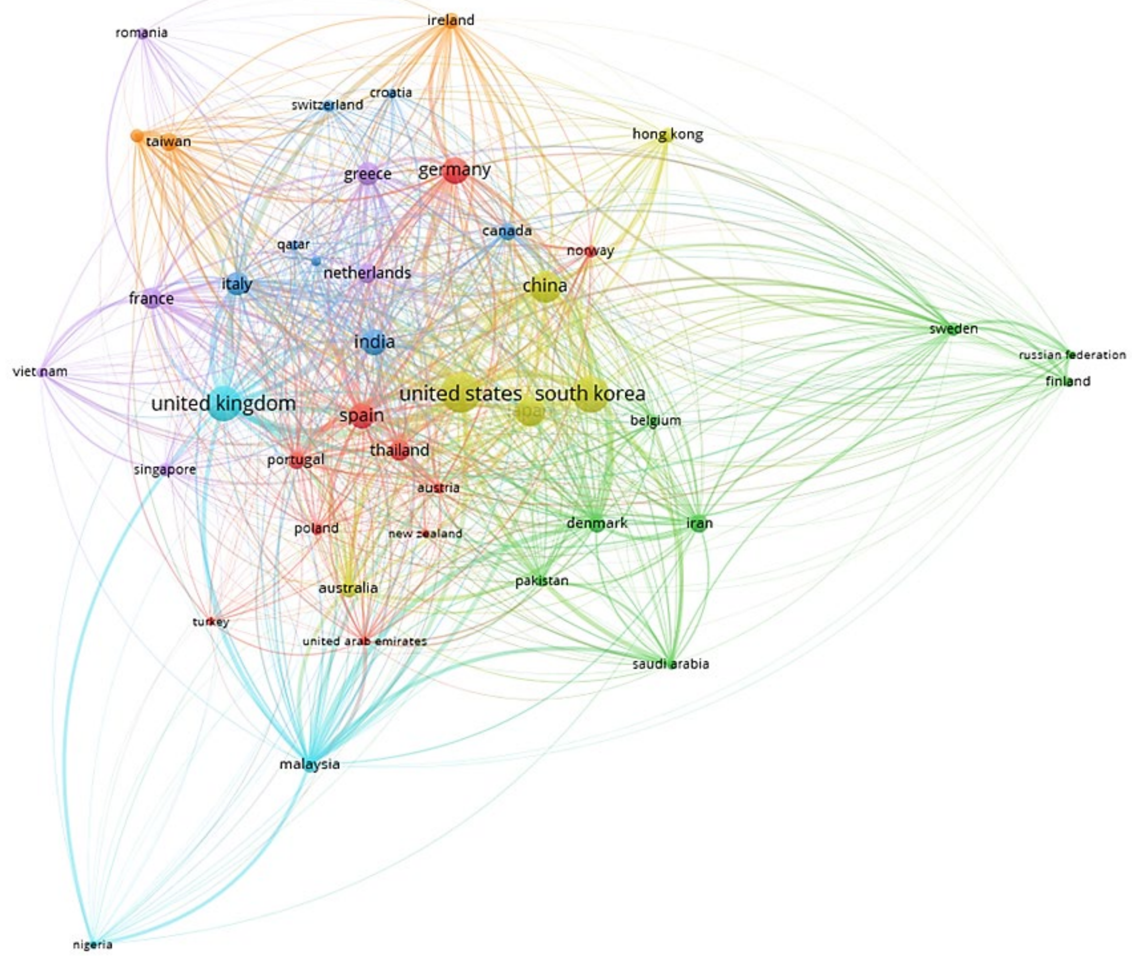

Figure 5. Bibliometric coupling analysis network research visualization of the country by VOSviewer.

geographic spread and intensity of BEMS research activities worldwide.

Figure 6 shows 43 countries, with the top 5 countries with the most published documents being the United States (115 publications), South Korea (93 publications), the United Kingdom (87 publications), China (70 publications), and Japan (62 publications). It is important to note that the number of documents does not necessarily reflect the quality or importance of the research. Other factors such as the size of the research community in a country and the level of government funding or affiliation for BEMS research can also play a role.

D. Science mapping by co-occurrence analysis

Science mapping by co-occurrence analysis shows the visualization of BEMS research keyword. Larger number of keywords indicate a higher frequency of occurrence in research publications. Different colors indicate groups of related keywords.

Figure 7 is a set of keyword overlay on BEMS publications from 1982 to 2024. Based on VOSviewer, the top 30 keyword research topics with the keyword energy management systems are energy management systems, building energy management systems, energy management, energy utilization, buildings, energy efficiency, building energy management system (BEMS), intelligent buildings, energy conservation, air conditioning, information management, office buildings, smart power grids, optimization, electric power transmission networks, automation demand response, building energy management, forecasting, internet of things, smart buildings, smart grids, three-term control systems, heating, ventilation, and air conditioning (HVAC), model predictive control, renewable energy resources, in-buildings, costs, housing and learning systems.

To make it easier to analyze the keywords used in the last four years during the 2020 - 2024 range. This visualization provides a clearer picture, as shown in Figure 8. Figure 8 shows the visualization of the citation keyword occurrence overlay with the range of 2020 to 2024, with the criteria for the minimum number of keyword occurrences of 5 out of 2,773 keywords that have been cleaned using open refine. 196 were found to meet the criteria threshold.

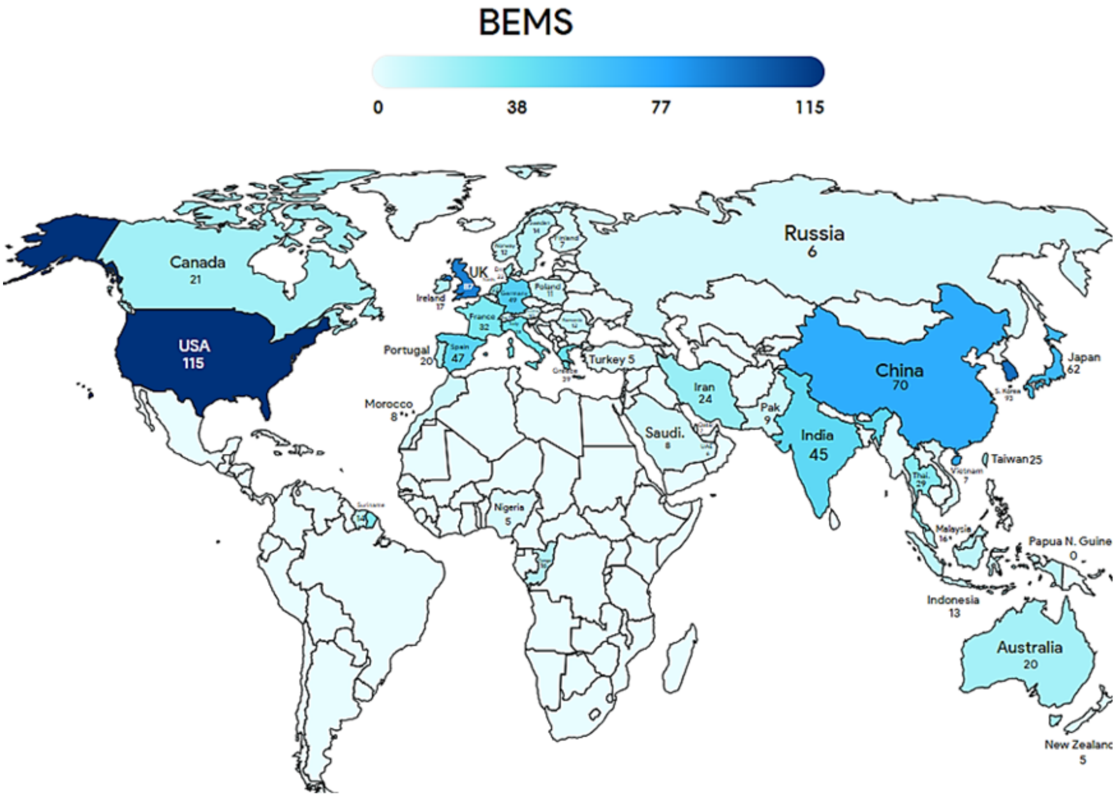

Figure 6. Visualization of BEMS research strength by country by iimaps.

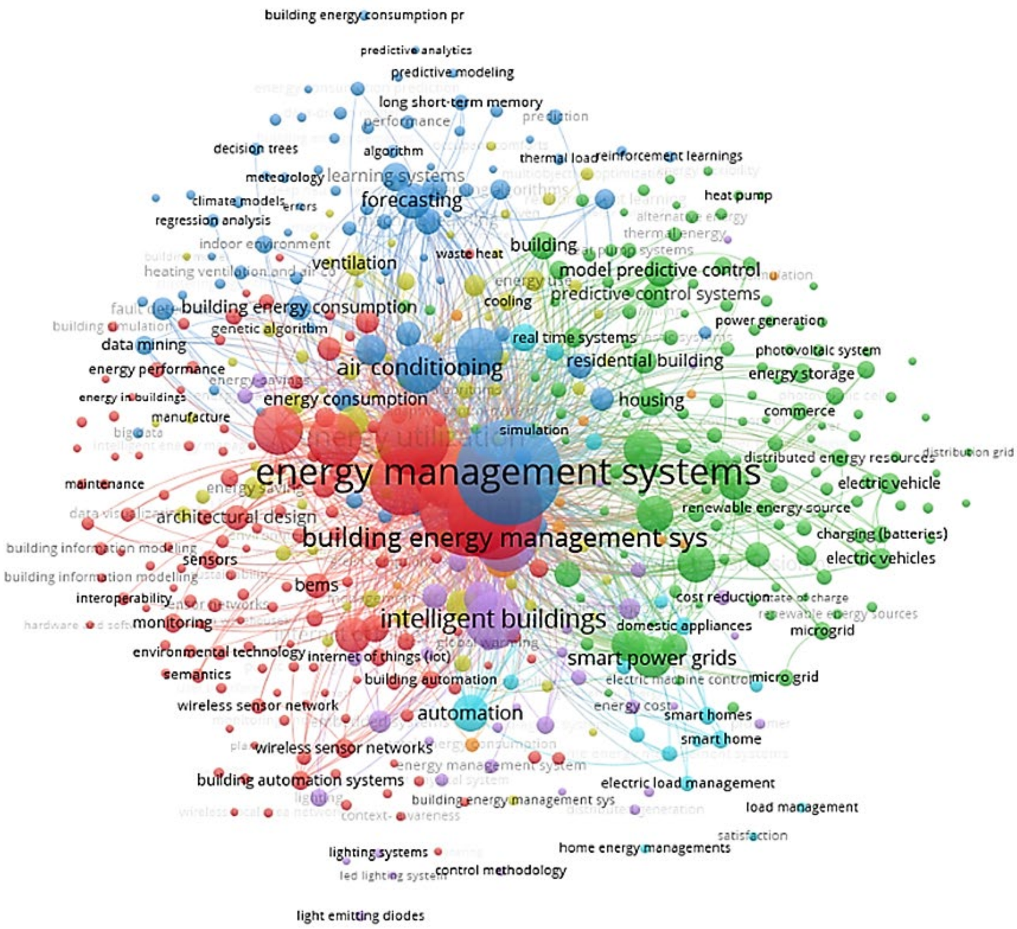

Figure 7. Keyword co-occurrence network in BEMS research (1982–2024).

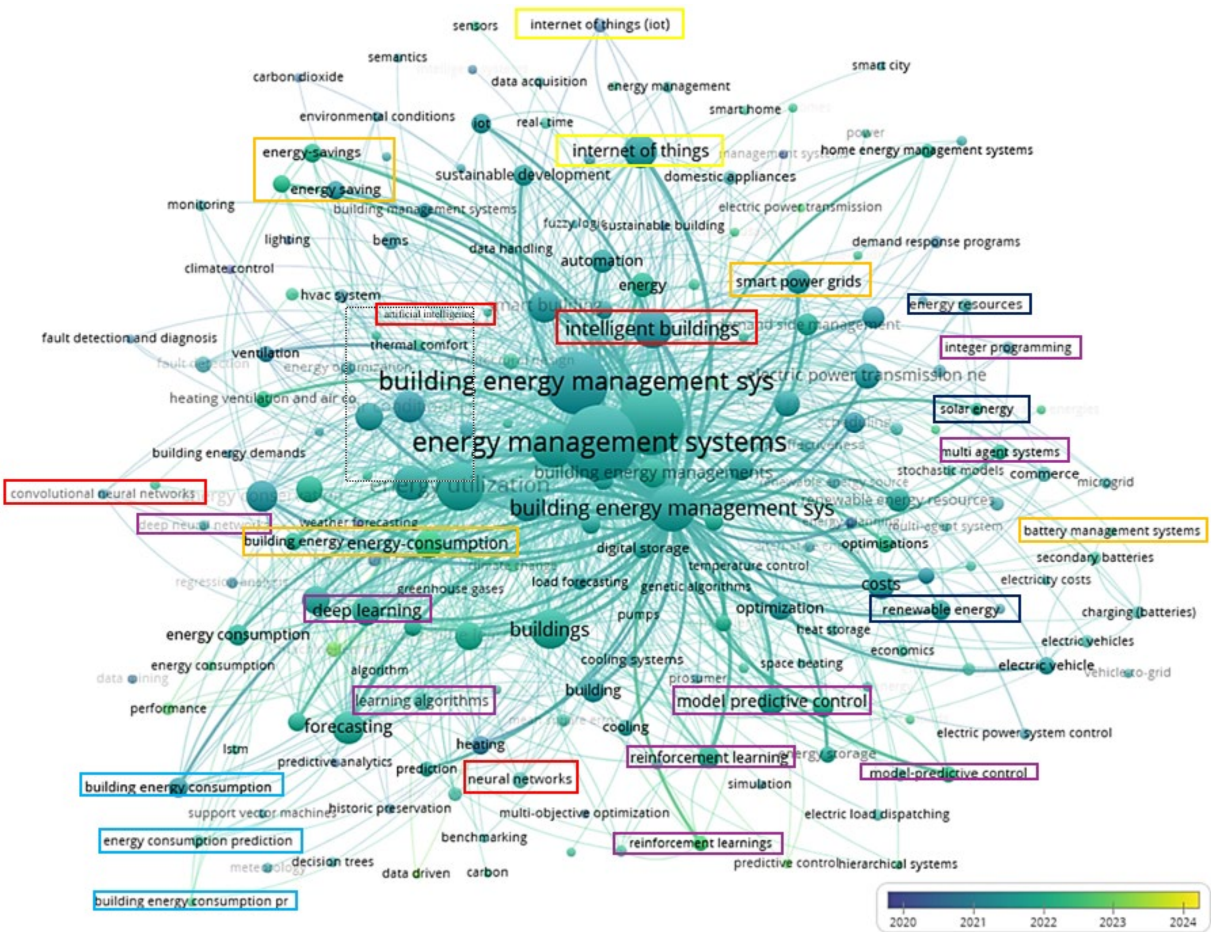

Figure 8. Recent keyword trends in BEMS research (2020–2024).

Table 5 shows 20 keywords co-occurrence regarding future research interest keyword topics on BEMS. BEMS research topics that will be widely published include building energy management systems, smart building, energy management, internet of things, energy efficiency, demand response, machine learning, deep learning, energy consumption, IoT, renewable energy, BEMS, energy saving, smart grid, electric vehicle, model predictive control, data-driven model, demand side management, artificial intelligence, and buildings. It is predicted that the development of BEMS technology will continue to grow and become more sophisticated. This allows BEMS to more effectively manage energy, especially sustainable energy, and improve energy efficiency.

E. Discussions

The findings of this bibliometric analysis reveal significant insights into the trends, challenges, and future directions of building energy management systems (BEMS) research. The rapid growth in publications and citations over the years indicates an increasing recognition of BEMS which is important in enhancing energy efficiency and sustainability in buildings. This trend is likely to continue as the

Table 5.
20 most frequently occurring keywords based on co-occurrence analysis of author keywords for 1982 – 2024.

Author keywords	Occurrence	Link strength
BEMS	92	142
Smart building	45	74
Energy management	39	74
Internet of things	31	51
Energy efficiency	26	51
Demand response	25	49
Machine learning	23	50
Deep learning	20	37
Energy consumption	17	23
IoT	15	26
Renewable energy	14	30
BEMS	13	16
Energy saving	13	32
Smart grid	13	38
Electric vehicle	12	26
Model predictive	12	23
Data-driven model	10	17
Demand management	10	27
Artificial intelligence	9	20
Buildings	9	9

demand for efficient energy solutions escalates in response to global climate change and urbanization.

The following is the answer for RQ1 regarding trends in BEMS research. BEMS research has evolved substantially since its inception in the early 1980s, with a notable acceleration in publications from 2010 onward. This growth reflects a heightened interest in energy management technologies and strategies, particularly in light of the pressing need for sustainable practices in the building sector. The emergence of advanced technologies, such as IoT and AI, has further catalyzed this growth, enabling more sophisticated and integrated BEMS solutions.

The answer for the RQ2 on influential BEMS publications is as follows. The identification of highly cited documents highlights the foundational works that have shaped the field of BEMS. Notably, the research by Dounis and Caraiscos (2009) [22] stands out as a critical contribution, providing a comprehensive review of advanced control systems for energy and comfort management. Such influential studies not only advance theoretical understanding but also guide practical implementations of BEMS in real-world scenarios.

As an attempt to answer RQ3, the geographical analysis reveals a concentration of BEMS research in a few key countries, notably the United States, South Korea, the United Kingdom, China, and Japan. This distribution suggests that these countries have established robust research communities and funding mechanisms to support BEMS initiatives. However, it also highlights the need for greater international collaboration and knowledge sharing, particularly in regions where BEMS research is still developing.

Addressing the keyword analysis and emerging themes in RQ4, the keyword co-occurrence analysis indicates a shift in focus within BEMS research towards intelligent energy management systems, integrating renewable energy sources, and utilizing smart technologies. Keywords such as "smart buildings," "IoT," and "energy efficiency" reflect the growing trend toward creating intelligent, adaptive environments that optimize energy use while enhancing occupant comfort. This shift underscores the importance of interdisciplinary approaches that combine engineering, computer science, and environmental studies.

Whereas in responding RQ5, the literatures reviewed emphasizes the multifaceted role of BEMS in improving energy efficiency and sustainability. By leveraging data from various sensors, BEMS can monitor energy use, optimize system performance, and integrate renewable energy sources, ultimately leading to reduced operational costs and environmental impact. The findings suggest that future research should focus on developing more affordable and user-friendly BEMS solutions, particularly for residential applications, to encourage wider adoption.

Based on the literature review of 2023-2024, BEMS is used to first improve energy efficiency and sustainability in buildings. BEMS works by optimizing the operation of various HVAC systems, lighting systems, and other equipment that use a IoT of energy. BEMS works to achieve energy efficiency and sustainability through monitoring and data collection. BEMS collects data from various sensors in the building [34][35][36], including temperature [34], humidity [34], occupancy levels [37], and energy consumption [38][39]. This data provides insight into how energy is used in the building. Second, control and optimization. Based on the collected data, the BMS can automatically adjust the settings of the HVAC system [34], lighting system [40], and other equipment to optimize energy use [41][42][43]. For example, the BMS can turn off lights in unoccupied spaces or adjust temperature settings based on outdoor temperatures [44][45][46] and occupancy levels [47][48][49]. Third, predictive maintenance. The BMS can analyze sensor data to identify potential equipment failures [41][44][50] and schedule preventive maintenance [51][52]. This can help avoid costly repairs and building operation downtime [53]. Fourth, integration with renewable energy sources. BMS can be integrated with renewable energy sources such as solar panels and battery storage systems [49][54][55]. This allows the building to utilize clean energy and reduce dependence on the power grid [56][57][58]. Fifth, improving occupant comfort. BMS can be used to create a more comfortable indoor environment for building occupants. For example, the BMS can adjust temperature and humidity levels based on occupant preferences [50][59][60] or equipment inside the room [61], and energy analysis of smart lighting systems should consider the visual comfort of the occupant [62][63][64].

For RQ6 challenges and opportunities despite the promising advancements in BEMS research, several challenges persist. The complexity of BEMS integration, lack of interoperability among systems from different vendors, cybersecurity vulnerabilities, and the scarcity of skilled professionals hinder the widespread implementation of these systems. Addressing these challenges requires collaborative efforts among researchers, industry stakeholders, and policymakers to develop standardized protocols, enhance cybersecurity measures, and provide training programs for professionals in the field.

Based on the literature review in the Scopus data set during 2023-2024, the main challenges and opportunities in research in the implementation of

BEMS are: first, system complexity: BEMS involves the integration of various components and technologies [50][57][65], such as a chiller, air handling unit (AHU), variable air volume (VAV), sensors [65], actuators, control software [48][50][57], metering [66], communication network [44], and renewable energy sources [48][55][67]. This can make BEMS systems complex and difficult to design, operate, and maintain. Second, lack of interoperability: BEMS systems from different vendors are often incompatible with each other, making it difficult to integrate and manage BEMS systems across multiple buildings [57][68][69]. Third, cybersecurity: BEMS systems are vulnerable to cyberattacks, which can disrupt operations and compromise sensitive data [70]. Fourth, lack of expertise: lack of experts skilled in the design, implementation, and operation of BEMS can hinder the adoption of this technology [68]. Fifth, cost: BEMS implementation can be expensive, especially for large and complex buildings [20].

The insights gained from this bibliometric analysis highlight the dynamic nature of BEMS research and its critical role in fostering sustainable building practices. By addressing existing challenges and capitalizing on emerging trends, BEMS has the potential to significantly contribute to a more energy-efficient and sustainable future for buildings.

IV. Conclusion

This study conducted a comprehensive bibliometric analysis of building energy management systems (BEMS) research, revealing significant trends, influential publications, and emerging themes from 1982 to 2024. The findings indicate a marked increase in research activity, particularly in the last decade, driven by the urgent need for sustainable energy solutions in the face of global climate change and urbanization. The analysis highlights several key insights. First, growth of BEMS research: the rapid expansion of publications and citations underscores the growing recognition of BEMS as a crucial tool for enhancing energy efficiency and sustainability in buildings. This trend is likely to continue as technological advancements and regulatory pressures push for smarter energy management solutions. Second, influential contributions: the identification of highly cited works reveals foundational studies that have shaped the field, providing valuable frameworks and methodologies for future research. These influential publications serve as critical resources for both researchers and practitioners seeking to implement effective BEMS solutions. Third, geographical insights: the concentration of BEMS research in specific countries indicates the presence of established research communities and funding opportunities. However, it also highlights the need for broader international collaboration to enhance knowledge sharing and innovation in BEMS technologies. Fourth, emerging themes and challenges: the analysis of keywords demonstrates a shift towards integrating advanced technologies such as IoT and AI within BEMS, reflecting that the industry is moving towards creating intelligent and adaptive building environments. Nonetheless, challenges such as interoperability, cybersecurity, and the need for skilled professionals remain significant barriers to widespread BEMS adoption. Fifth, future directions: to fully realize the potential of BEMS, future research must focus on addressing the identified challenges, developing cost-effective and user-friendly solutions, and exploring the integration of BEMS with other emerging technologies. This will facilitate broader implementation across various building types, particularly in the residential sector, where energy efficiency gains can have a substantial impact. In summary, this study contributes to the understanding of BEMS research by mapping its evolution and identifying key areas for future exploration. By addressing the challenges and leveraging emerging trends, BEMS can play a pivotal role in promoting a more sustainable and energy-efficient future for buildings worldwide.

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Declarations

Author contribution

V. Sihombing: literature searching, formal analysis, writing original draft. **E. Yandri**: supervision, resources, conceptualization, methodology. **K.P. Pramono**: editing, drawing, validation. **R. Ariati**: resources, correction.

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The author declares that there is no conflict of interest regarding the publication of this article.

References

[1] Y. Yuan *et al.*, "A novel multi-step Q-learning method to improve data efficiency for deep reinforcement learning," *Knowledge-Based Syst.*, vol. 175, no. July, pp. 107–117, 2019.

[2] A. Y. Nageye, A. D. Jimale, M. O. Abdullahi, Y. A. Ahmed, and B. S. A. Jama, "Enhancing energy efficiency in Mogadishu: IoT-based buildings energy management system," *SSRG Int. J. Electr. Electron. Eng.*, vol. 10, no. 10, pp. 54–60, 2023.

[3] A. Irawan *et al.*, "An energy optimization study of the electric arc furnace from the steelmaking process with hot metal charging," *Heliyon*, vol. 8, no. 11, p. e11448, 2022.

[4] A. Chojecki, A. Ambroziak, and P. Borkowski, "Fuzzy controllers instead of classical PIDs in HVAC equipment: Dusting off a well-known technology and today's implementation for better energy efficiency and user comfort," *Energies*, vol. 16, no. 7, p. 2967, Mar. 2023.

[5] E. Yandri *et al.*, "Implementation of walk-through audits for designing energy management system: A first step towards an efficient campus," *IOP Conf. Ser. Earth Environ. Sci.*, vol. 490, no. 1, p. 012005, Apr. 2020.

[6] M. Rumbayan, I. Pundoko, D. Ruindungan, and N. V. Panjaitan, "Development of internet of things-based monitoring system for application solar energy technology in Bunaken island," *IOP Conf. Ser. Earth Environ. Sci.*, vol. 1041, no. 1, p. 012023, Jun. 2022.

[7] T. Mega, K. Murakami, and N. Kushiro, "BEMS architecture and service modules for realizing sophisticated algorithms," *Electron. Commun. Japan*, vol. 106, no. 4, p. 32, Dec. 2023.

[8] M. Hossain, Z. Weng, R. Schiano-Phan, D. Scott, and B. Lau, "Application of IoT and BEMS to visualise the environmental performance of an educational building," *Energies*, vol. 13, no. 15, p. 4009, Aug. 2020.

[9] K. Song, Y. Jang, M. Park, H. Lee, and J. Ahn, "Energy efficiency of end-user groups for personalized HVAC control in multi-zone buildings," *Energy*, vol. 206, p. 118116, Sep. 2020.

[10] E. Yandri *et al.*, "Recent research progress on sustainable energy management system based on energy efficiency and renewable energy," *BIO Web Conf.*, vol. 104, p. 00012, May 2024.

[11] O. Pedram, E. Asadi, B. Chenari, P. Moura, and M. Gameiro da Silva, "A review of methodologies for managing energy flexibility resources in buildings," *Energies*, vol. 16, no. 17, p. 6111, Aug. 2023.

[12] A. T. Dahiru, D. Daud, C. W. Tan, Z. T. Jagun, S. Samsudin, and A. M. Dobi, "A comprehensive review of demand side management in distributed grids based on real estate perspectives," *Environ. Sci. Pollut. Res.*, vol. 30, no. 34, pp. 81984–82013, 2023.

[13] D. Mariano-Hernández, L. Hernández-Callejo, A. Zorita-Lamadrid, O. Duque-Pérez, and F. Santos García, "A review of strategies for building energy management system: Model predictive control, demand side management, optimization, and fault detect & diagnosis," *J. Build. Eng.*, vol. 33, p. 101692, Jan. 2021.

[14] A. Ahmi, "Bibliometric analysis for beginners," in *Bibliometric Analysis for Beginners*, Book Pre-P., A. Ahmi, Ed., Malaysia, 2021, pp. 1–180. [Online].

[15] N. Donthu, S. Kumar, D. Mukherjee, N. Pandey, and W. M. Lim, "How to conduct a bibliometric analysis: An overview and guidelines," *J. Bus. Res.*, vol. 133, no. May, pp. 285–296, 2021.

[16] I. Bernatović, A. Slavec Gomezel, and M. Černe, "Mapping the knowledge-hiding field and its future prospects: a bibliometric co-citation, co-word, and coupling analysis," *Knowl. Manag. Res. Pract.*, vol. 20, no. 3, pp. 394–409, 2022.

[17] D. Mukherjee, W. M. Lim, S. Kumar, and N. Donthu, "Guidelines for advancing theory and practice through bibliometric research," *J. Bus. Res.*, vol. 148, no. May, pp. 101–115, 2022.

[18] W. M. Lim and S. Kumar, "Guidelines for interpreting the results of bibliometric analysis: A sensemaking approach," *Glob. Bus. Organ. Excell.*, vol. 43, no. 2, pp. 17–26, 2024.

[19] F. Rezazadeh and N. Bartzoudis, "A federated DRL approach for smart micro-grid energy control with distributed energy resources," in *2022 IEEE 27th International Workshop on Computer Aided Modeling and Design of Communication Links and Networks (CAMAD)*, IEEE, Nov. 2022, pp. 108–114.

[20] J. Hossain et al., "A review on optimal energy management in commercial buildings," *Energies*, vol. 16, no. 4, 2023.

[21] S. Alawadi, D. Mera, M. Fernández-Delgado, F. Alkhabbas, C. M. Olsson, and P. Davidsson, "A comparison of machine learning algorithms for forecasting indoor temperature in smart buildings," *Energy Syst.*, vol. 13, no. 3, pp. 689–705, 2022.

[22] A. I. Dounis and C. Caraiscos, "Advanced control systems engineering for energy and comfort management in a building environment—A review," *Renew. Sustain. Energy Rev.*, vol. 13, no. 6–7, pp. 1246–1261, Aug. 2009.

[23] P. Du and N. Lu, "Appliance commitment for household load scheduling," *IEEE Trans. Smart Grid*, vol. 2, no. 2, pp. 411–419, Jun. 2011.

[24] E. Mocanu *et al.*, "On-line building energy optimization using deep reinforcement learning," *IEEE Trans. Smart Grid*, vol. 10, no. 4, pp. 3698–3708, Jul. 2019.

[25] H. Doukas, K. D. Patlitzianas, K. Iatropoulos, and J. Psarras, "Intelligent building energy management system using rule sets," *Build. Environ.*, vol. 42, no. 10, pp. 3562–3569, Oct. 2007.

[26] M. W. Ahmad, M. Mourshed, D. Mundow, M. Sisinni, and Y. Rezgui, "Building energy metering and environmental monitoring – A state-of-the-art review and directions for future research," *Energy Build.*, vol. 120, pp. 85–102, May 2016.

[27] R. Missaoui, H. Joumaa, S. Ploix, and S. Bacha, "Managing energy smart homes according to energy

prices: Analysis of a building energy management system," *Energy Build.*, vol. 71, pp. 155–167, Mar. 2014.

[28] D. Lee and C.-C. Cheng, "Energy savings by energy management systems: A review," *Renew. Sustain. Energy Rev.*, vol. 56, pp. 760–777, Apr. 2016.

[29] F. Wang *et al.*, "Multi-objective optimization model of source–load–storage synergetic dispatch for a building energy management system based on TOU price demand response," *IEEE Trans. Ind. Appl.*, vol. 54, no. 2, pp. 1017–1028, Mar. 2018.

[30] P. Zhao, S. Suryanarayanan, and M. G. Simoes, "An energy management system for building structures using a multi-agent decision-making control methodology," in *2010 IEEE Industry Applications Society Annual Meeting*, IEEE, Oct. 2010, pp. 1–8.

[31] M. A. Hannan *et al.*, "A review of internet of energy based building energy management systems: issues and recommendations," *IEEE Access*, vol. 6, no. september 2016, pp. 38997–39014, 2018.

[32] D. Kolokotsa, A. Pouliezos, G. Stavrakakis, and C. Lazos, "Predictive control techniques for energy and indoor environmental quality management in buildings," *Build. Environ.*, vol. 44, no. 9, pp. 1850–1863, Sep. 2009.

[33] H. Doukas, K. D. Patlitzianas, K. Iatropoulos, and J. Psarras, "Intelligent building energy management system using rule sets," *Build. Environ.*, vol. 42, no. 10, pp. 3562–3569, Oct. 2007.

[34] D. F. Espejel-Blanco, J. A. Hoyo-Montano, J. M. Chavez, and F. A. Hernandez-Aguirre, "Environment sensor node design for building energy management systems (BEMS)," in *2023 IEEE Conf. Technol. Sustain. (SusTech)*, pp. 99–103, 2023.

[35] N. T. Ngo, N. S. Truong, T. T. H. Truong, A. D. Pham, and N. T. Huynh, "Implementing a web-based optimized artificial intelligence system with metaheuristic optimization for improving building energy performance," *J. Asian Archit. Build. Eng.*, vol. 23, no. 1, pp. 264–281, 2024.

[36] A. Fetanat, M. Tayebi, G. Shafipour, and M. Moteraghi, "A novel integrated method of fsQCA and digital design for sustainability monitoring and assessment in building energy management systems: a case study," *J. Build. Perform. Simul.*, vol. 16, no. 1, pp. 107–130, 2023.

[37] J. G. B. Abad, D. G. Romero, J. M. Dolalas, R. C. Parocha, and E. Q. B. Macabebe, "MQTT based appliance control and automation with room occupancy monitoring using YOLO," in *Lecture Notes in Networks and Systems*, 2022, pp. 757–770.

[38] L. Ma, Y. Huang, and T. Zhao, "A synchronous prediction method for hourly energy consumption of abnormal monitoring branch based on the data-driven," *Energy Build.*, vol. 260, p. 111940, Apr. 2022.

[39] O. B. M. Magtibay, R. H. Cabrera, J. P. Roxas, and M. A. de Vera, "Green switch: An IoT based energy monitoring system for mabini building in De La Salle Lipa," *Indones. J. Electr. Eng. Comput. Sci.*, vol. 24, no. 2, pp. 754–761, 2021.

[40] O. Kotevska and P. Andelfinger, "Reinforcement learning for intelligent building energy management system control*," in *Intelligent Data Mining and Analysis in Power and Energy Systems*, Wiley, 2022, pp. 371–386.

[41] M. Subramaniam A., T. Jain, and J. J. Yamé, "Bilinear observer-based robust adaptive fault estimation for multizone building VAV terminal units," J. Build. Perform. Simul., vol. 16, no. 6, pp. 717–733, Nov. 2023.

[42] D. P. Finn and C. J. Doyle, "Control and optimization issues associated with algorithm-controlled refrigerant throttling devices," in *ASHRAE Transactions*, 2000. [Online].

[43] A. Burda, D. Bitner, F. Bestehorn, C. Kirches, and M. Grotjahn, "Mixed-integer real-time control of a building energy supply system," *IEEE Control Syst. Lett.*, vol. 7, pp. 907–912, 2023.

[44] A. Banjac, H. Novak, and M. Vašak, "Implementation of model predictive indoor climate control for hierarchical building energy management," *Control Eng. Pract.*, vol. 136, no. september 2016, p. 105536, Jul. 2023.

[45] C. Zhang, Y. Shi, and Y. Chen, "BEAR: physics-principled building environment for control and reinforcement learning," in *14th ACM Int. Conf. Futur. Energy Syst. (e-Energy 2023)*, pp. 66–71, 2023.

[46] K. Kurte, K. Amasyali, J. Munk, and H. Zandi, "Deep reinforcement learning with online data augmentation to improve sample efficiency for intelligent HVAC control," in *Proceedings of the 9th ACM International Conference on Systems for Energy-Efficient Buildings, Cities, and Transportation*, New York, NY, USA: ACM, Nov. 2022, pp. 479–483.

[47] S. Mohan Krishna, T. Perumal, S. Surya, and Chandrashekar, "Interoperability in IoT-driven smart buildings," in *Internet of Things in Modern Computing*, no. september 2016, Boca Raton: CRC Press, 2023, pp. 133–142.

[48] H. Agharazi *et al.*, "Installation and testing of a two-level model predictive control building energy management system," *IEEE Trans. Control Syst. Technol.*, vol. 32, no. 2, pp. 326–339, Mar. 2024.

[49] H. Elehwany, M. Ouf, B. Gunay, N. Cotrufo, and J.-S. Venne, "A reinforcement learning approach for thermostat setpoint preference learning," *Build. Simul.*, vol. 17, no. 1, pp. 131–146, Jan. 2024.

[50] A. A. bin Mohd Ameeruddin, W.-N. Tan, M.-T. Gan, and S.-C. Yip, "Predictive AC control using deep learning: improving comfort and energy saving," *JOIV Int. J. Informatics Vis.*, vol. 7, no. 3–2, p. 1066, Nov. 2023.

[51] M. Habib, E. Bollin, and Q. Wang, "battery energy management system using edge-driven fuzzy logic," *Energies*, vol. 16, no. 8, 2023.

[52] R. Selvaraj, V. M. Kuthadi, and S. Baskar, "Smart building energy management and monitoring system based on artificial intelligence in smart city," *Sustain. Energy Technol. Assessments*, vol. 56, p. 103090, Mar. 2023.

[53] S. Sarkar, A. Karthick, V. Kumar Chinnaiyan, and P. P. Patil, "Energy forecasting of the building-integrated photovoltaic façade using hybrid LSTM," *Environ. Sci. Pollut. Res.*, vol. 30, no. 16, pp. 45977–45985, Jan. 2023.

[54] E. Zarate-Perez, C. Santos-Mejía, and R. Sebastián, "Global trends in building energy management systems (BEMS): A science mapping approach," in *AIP Conference Proceedings*, 2023, p. 020038.

[55] S. Yang, H. Oliver Gao, and F. You, "Model predictive control in phase-change-material-wallboard-enhanced building energy management considering electricity price dynamics," *Appl. Energy*, vol. 326, p. 120023, Nov. 2022.

[56] Z. Hu, Y. Gao, S. Ji, M. Mae, and T. Imaizumi, "Improved multistep ahead photovoltaic power prediction model based on LSTM and self-attention with weather forecast data," *Appl. Energy*, vol. 359, p. 122709, Apr. 2024.

[57] A. Jozi, T. Pinto, L. Gomes, G. Marreiros, and Z. Vale, "rule-based system for intelligent energy management in buildings," in *Экономика Региона*, 2023, pp. 169–181.

[58] M. F. Faiz, M. Sajid, S. Ali, K. Javed, and Y. Ayaz, "Energy modeling and predictive control of environmental quality for building energy management using machine learning," *Energy Sustain. Dev.*, vol. 74, pp. 381–395, Jun. 2023.

[59] M. Ye, A. A. Serageldin, H. Sato, and K. Nagano, "Field study on indoor thermal comfort of a 'ZEB Ready' office building using radiant ceiling panel coupled with open-loop ground source heat pump," in *Environmental Science and Engineering (ESE)*, 2023, pp. 2353–2362.

[60] M. Roccotelli, A. Rinaldi, M. P. Fanti, and F. Iannone, "Building energy management for passive cooling based on stochastic occupants behavior evaluation," *Energies*, vol. 14, no. 1, p. 138, Dec. 2020.

[61] N. Bucarelli and N. El-Gohary, "Deep learning approach for recognizing cold and warm thermal discomfort cues from videos," *Build. Environ.*, vol. 242, no. september 2016, p. 110277, Aug. 2023.

[62] M. K. Yadav, A. Rampal, A. Verma, and B. K. Panigrahi, "Energy analysis of smart lighting system considering visual comfort of occupants for educational building," in *2019 International Conference on Computing, Power and Communication Technologies (GUCON 2019)*, 2019, pp. 572–577. [Online].

[63] A. Das, M. K. Annaqeeb, E. Azar, V. Novakovic, and M. B. Kjærgaard, "Occupant-centric miscellaneous electric loads prediction in buildings using state-of-the-art deep learning methods," *Appl. Energy*, vol. 269, p. 115135, Jul. 2020.

[64] A. Boodi, K. Beddiar, M. Benamour, Y. Amirat, and M. Benbouzid, "Intelligent systems for building energy and occupant comfort optimization: A state of the art review and recommendations," *Energies*, vol. 11, no. 10, 2018.

[65] N. Daurenbayeva, L. Atymtayeva, and A. Nurlanuly, "Choosing the intelligent thermostats for the effective decision making in BEMS," in *2023 17th International Conference on Electronics Computer and Computation (ICECCO)*, IEEE, Jun. 2023, pp. 1–4.

[66] E. Saloux and K. Zhang, "Towards integration of virtual meters into building energy management systems: Development and assessment of thermal meters for cooling," *J. Build. Eng.*, vol. 65, p. 105785, Apr. 2023.

[67] M. Amin, G. A. Abdel Aziz, M. Naraghi, M. Palatty, A. Benz, and D. Ruiz, "Improving the data center servers cooling efficiency via liquid cooling-based heat pipes," in *2020 IEEE Ind. Appl. Soc. Annu. Meet.*, pp. 3–7, 2020.

[68] L. Desmomd and M. Salama, "Integrating blockchain & emerging technologies for sustainability assurance in the built environment," in *2023 IEEE International Conference on Artificial Intelligence, Blockchain, and Internet of Things (AIBThings)*, IEEE, Sep. 2023, pp. 1–5.

[69] P. Yefi, R. Menon, and U. Eicker, "Building IoT systems modeling: An object-oriented metamodeling approach," in *2023 IEEE/ACM 5th International Workshop on Software Engineering Research and Practices for the IoT (SERP4IoT)*, IEEE, May 2023, pp. 1–8.

[70] J. Lim, W. Ong, U. Tefek, and E. Esiner, "A security policy engine for building energy management systems," in *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, 2023, pp. 231–244.