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Evolving Trends in Energy Management Systems (EMS) Research Using Scientometric Analysis

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ABSTRACT

Energy Management Systems (EMS) play a vital role in optimizing energy usage, reducing environmental impact, and enhancing energy efficiency in both microgrid and residential applications. The increasing complexity of energy systems, coupled with advancements in artificial intelligence (AI) and demand response mechanisms, has led to rapid evolution in EMS research. However, this progress has resulted in fragmented knowledge, making it difficult to discern overarching trends and identify key contributions in the field. This study addresses the following questions: What are the major trends, influential works, and future directions in EMS research over the past five decades? To answer this, a comprehensive scientometric analysis of 3,709 publications (1973–2023) was conducted using the Web of Science database and analyzed through CiteSpace. The analysis reveals significant shifts in EMS research, transitioning from traditional microgrid-focused studies to broader applications in smart homes, AI-driven load scheduling, and advanced optimization techniques. Key findings highlight the growing emphasis on integrating AI, machine learning, and real-time decision-making to enhance the responsiveness and sustainability of EMS. Additionally, the study identifies critical contributions from influential publications that provide a roadmap for developing next-generation EMS frameworks. These works emphasize the importance of addressing emerging challenges, such as the need for adaptive load management, enhanced grid stability, and increased reliance on renewable energy sources. By synthesizing historical trends and future directions, this study offers valuable insights for researchers, practitioners, and policymakers to advance innovations in energy management, contributing to a more sustainable and efficient energy landscape.

Keywords: Energy management systems; environmental impact; sustainability; scientometric analysis

INTRODUCTION

The development and progression of Energy Management Systems (EMS) have been closely tied to the growing global need to address energy efficiency, sustainability, and the environmental impacts of energy consumption. However, awareness and adoption of EMS, particularly in developing regions, remain limited despite increasing energy demands and environmental concerns (Basri et al. 2021). This parallel development aligns with global awareness and priorities, driven by factors such as escalating energy costs, growing environmental concerns, and the imperative to optimize energy resources in the context of sustainable practices. EMS has emerged as a pivotal solution within this complex landscape, designed to facilitate comprehensive control, monitoring, and optimization of energy usage, thereby aligning industrial, commercial, and residential sectors with the objectives of energy conservation and environmental responsibility. EMS is a necessary mechanism for smart grids to effectively implement demand-side management (Mousa Marzband et al. 2013; Zhou et al. 2016; ur Rehman et al. 2023). Using a human–machine interface, it continuously monitors and arranges different appliances according to the user's preferences to reduce the cost of electricity and increase the efficiency of energy consumption (Bonilla et al. 2018; Lee 2020). The idea originated from the recognition of the need to reduce operational expenses while enhancing industry efficiency and stressing sustainable practices characteristics (ur Rehman et al. 2023; Mischos et al. 2023). Rather than viewing end users as passive actors in the consumption process, it aims to facilitate more active end-user participation.

The usage of EMS has increased due to the issue of the energy crisis and the steadily rising load demand. These systems are an essential organizational and technological strategy for maximizing energy use, cutting expenses, and minimizing environmental impact. Recent research indicates a growing emphasis on the usage of Energy Systems Management (ESM) as distribution generation, energy storage, and electric vehicles, with the goal of providing sustainable, economically viable, and dependable energy solutions (Chavda et al. 2022; Muqeet et al. 2022). There is also a wave of studies centered on improving microgrid efficiency through the introduction of EMS (Charoen et al. 2022; Zia et al. 2022).

Furthermore, several comprehensive reviews have collectively addressed vital concerns within the energy management field. There are systematic reviews underscore the significance of optimizing energy utilization in residential and non-residential buildings, emphasizing the role of energy management systems like Home Energy Management Systems (HEMS) (ur Rehman et al. 2023; Mischos et al. 2023). Another review highlights the integration of renewable energy sources, particularly in microgrids and smart cities, underscoring the necessity for effective energy management techniques in these evolving energy landscapes (Thirunavukkarasu et al. 2022; Gomes et al. 2022). Yet another review delves into the connection between energy wastage, CO2 emissions, and climate change, underscoring the importance of intelligent EMS in mitigating these issues (Farshad Etedadi Aliabadi et al. 2021; Mischos et al. 2023). Lastly, some reviews focus on the various designs of EMS in buildings (Ahmed & Khitab, 2021) and their capacity to perform multiple functions, shedding light on the crucial aspects of control and optimization for energy savings (Al-Ghaili et al. 2021; Mariano-Hernández et al. 2021).

It is essential to recognize that while these literature reviews provide valuable insights into EMS research, they have inherent limitations. One significant drawback is their tendency to focus narrowly on specific issues or disciplines, a limitation arising from the labor-intensive process of sifting through a substantial volume of publications, identifying key concepts and drawing meaningful conclusions. To address this limitation and gain a broader perspective, Scientometrics, a quantitative method for evaluating scientific performance, is employed. This approach has been utilized in various research areas, such as thermal tolerance areas, aquaculture studies, and solar energy research (Azra et. al. (2022); Iqbal et. al. (2022); Mohd Noor et. al. (2023). Scientometrics encompasses diverse quantitative techniques, from basic descriptive statistics and data visualization to advanced methods like network analysis, machine learning algorithms, mathematical analysis, and computer simulation. In this study, the aim is to synthesize EMS research published between 1976 and 2023 using the Web of Science (WoS) database and the scientometric tool, CiteSpace. This research seeks to answer several key questions: (i) What are the overall publication trends in terms of output? (ii) What are the central topics/clusters? and (iii) What are the most influential publications in these domains?

While substantial progress has been made in various EMS applications, including microgrids, smart homes, and renewable energy integration, the existing research landscape remains fragmented, lacking a holistic view of its trends and advancements. This paper makes several key contributions to address this gap. First, it provides a comprehensive scientometric analysis of EMS research spanning five decades, uncovering the evolution of key themes and publication trends. Second, it identifies the most influential publications and their contributions to shaping EMS discourse, offering insights into foundational studies and emerging areas of interest. Lastly, it proposes a roadmap for future research, emphasizing the integration of advanced technologies, the importance of interdisciplinary collaboration, and the need to address policy and economic challenges in energy management.

To provide a structured narrative, the paper is organized as follows. The next section highlights the methodology section, which details the scientometric approach and data analysis techniques employed. The results and discussion section presents key findings, including trends in publications, influential clusters, and thematic areas, and discusses their implications for the field. Finally, the conclusion summarizes the main contributions of the paper, acknowledges its limitations, and offers directions for future research. This structure ensures a logical flow of ideas and enhances the accessibility of the findings to readers across academic and industry backgrounds.

METHODOLOGY

This study employed the scientometric method to examine the journal articles in WoS database that were published between the years 1976 to 2023 which used EMS as its research focus.

DATABASE SEARCHES

Data for this study was systematically gathered from the WoS core collection database provided by Clarivate Analytics, a widely recognized and highly reputable source for comprehensive scholarly information. The WoS database is commonly utilized in various research fields, particularly in scientometrics, due to its extensive coverage across diverse knowledge areas. It stands out for its ability to rank countries, journals, scientists, papers, and institutions by research field. This database encompasses over 6,650 prominent journals spanning 150 scientific disciplines, including all cited references from indexed articles (Azra et. al. (2022); Iqbal et. al. (2022); Mohd Noor et. al. (2023).

The search in WoS was conducted using a well-defined keyword (search code), complemented by an asterisk "*" placed at the end of the search code to encompass variations and broaden the search scope. WoS explored the titles of manuscripts, abstracts, keywords, author names, and Keywords Plus when the "TS" field was selected for searching. The final search code used for this study was "TS= ("energy management system")." The search was confined to articles published between 1976 and 2023, with a focus on original research articles. Articles falling under categories like commentaries, short communications, books, book chapters, protocol papers, theory/discussion papers, and editorials were excluded from consideration. This inclusive approach allowed for the inclusion of diverse research designs, encompassing quantitative, qualitative, and mixed-methods studies. The search was executed on October 10, 2023.

DATABASE ANALYSIS

Data analysis will be broken down into two types of analysis: (i) Descriptive Analysis and (ii) Scientometric Analysis. The explanation for both analysis is given below. The methodology of our literature search is summarized in the flowchart in Figure 1.

DESCRIPTIVE ANALYSIS

Descriptive analysis was performed on number of papers that were published annually, the names of the journals wherein the papers were published, and the names of the most productive authors, universities/institutes, and countries wherein the authors were residing when the papers were published.

SCIENTOMETRIC ANALYSIS

CiteSpace 6 version 6.2 for 64-bit Windows was used to conduct visualization and knowledge graph analysis in this study. CiteSpace offers the most comprehensive suite of tools for generating multiple bibliometric networks and conducting multiple methods of analysis. In this study, the scientometric analysis is broken down into two types of analysis: (i) dual-map overlay and (ii) document co-citation analysis (Chen et al. 2009; Chen & Leydesdorff, 2013; Chen & Song, 2019).

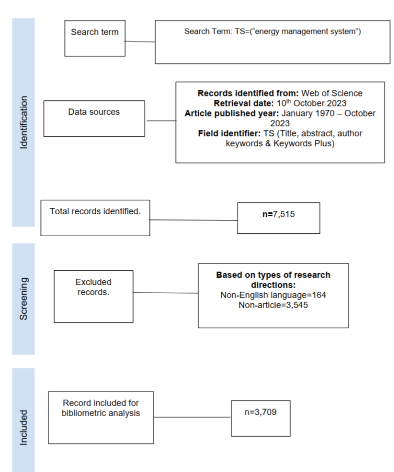

FIGURE 1. Methodological framework for the current study

The dual-map overlay analysis involved the categorization of literature into two distinct groups: (1) cited journals and (2) citing journals, where the latter cited references from the former. This analysis visually represented and quantified the strength of connections between these two groups. It effectively showcased the positioning of journals within the specific dataset on a global landscape. This process entailed tracking the cited journals found in the reference lists of other journals and placing them on a separate journal overlay map, subsequently linking both maps. The ovals on the map denoted clusters of highly active citing and cited journals, with their sizes corresponding to the number of publications for the citing journals on the left and the number of citations received on the right. Therefore, the left side of the map illustrated the distribution of journals focusing on EMS areas within the global landscape, while the right side represented the distribution of cited journals. The thickness of the lines bridging the cited and citing maps indicated the frequency of citation, with thicker lines (adjusted with z-scores) signifying a higher frequency of citing between disciplines (Chen et al. 2009; Chen & Leydesdorff, 2013; Chen & Song, 2019).

Then, Document Co-citation Analysis (DCA) was conducted, where co-citation instances occur when two sources are cited together in a single paper. The DCA results were presented in terms of both individual articles and clustered articles. For individual articles, DCA outcomes included burstness, centrality, and sigma. The burstness indicated sudden spikes in citations for specific articles, reflecting the number of citations received in particular years. Centrality scores identified the most influential articles in the research domain, with higher scores signifying a stronger influence in the network as these articles connected more publications and journals, facilitating the flow of information. Articles with centrality values exceeding 1 were considered "central" publications, acting as bridges for other publications in the EMS network. Sigma, a metric ranging from 0 to 1, combined centrality and burstness to gauge scientific novelty. It identified and measured innovative ideas presented in scientific publications, with higher values associated with more impactful research (Chen et al. 2009; Chen & Leydesdorff, 2013; Chen & Song, 2019).

In the context of DCA clusters, a multidimensional clustering method was employed to identify clusters, using the Log-Likelihood Ratio (LLR) to automatically extract cluster labels. This approach was selected for its optimal results in terms of uniqueness and coverage. To visualize the network's structure and evolution, the study utilized both a timeline view, featuring vertical lines representing chronological time zones, and a cluster view, which presented spatial network representations color-coded and auto labelled in a landscape format. To evaluate the quality and coherence of the analysis and the clusters, two key metrics were employed. Modularity Q index, which ranges from 0 to 1, with higher values signifying greater reliability and Silhouette Metric, which spans from -1 to 1, with positive values above 0 indicating enhanced cluster coherence and homogeneity (Chen et al. 2009; Chen & Leydesdorff, 2013; Chen & Song, 2019).

RESULTS

DESCRIPTIVE RESULT

EVOLUTION OF PUBLISHED STUDIES

In total, our search as outlined in the methodology section, retrieved 3,708 publications that collectively boast an impressive h-index of 130. These publications have been cited 98,600 times, resulting in an average citation rate of 26.59 citations per article. Table 1 illustrates the trajectory of EMS research spanning from 1973 to 2023, revealing an upward trend. Additionally, Table 1 underscores the growth in publications centered on EMS, projecting continued advancement in this research domain. Notably, prior to 2007, annual publication numbers remained under 10. However, a significant surge in the number of publications emerged in 2008. Subsequently, annual publications increased substantially, reaching 582 in 2022, with an average of 310 articles published from 2013 to 2023, as depicted in Table 1.

TABLE 1. Number of research articles regarding Energy Management Systems published annually since 1973

Publication Years	Number of Articles	Publication Years	Number of Articles
1976	2	2002	4
1978	1	2003	8
1979	1	2004	7
1980	3	2005	8
1981	4	2006	8
1984	2	2007	9
1985	3	2008	16
1986	1	2009	25
1987	6	2010	22
1988	2	2011	40
1989	1	2012	62
1990	2	2013	82
1991	4	2014	108
1992	9	2015	134

continue ...

... cont.

1993	3	2016	187
1994	2	2017	248
1995	2	2018	295
1996	1	2019	401
1997	10	2020	453
1998	7	2021	541
1999	6	2022	582
2000	5	2023	389
2001	2		

Table 2 provides an overview of the countries actively contributing to research in the field of EMS. A total of 106 countries have participated in this area, with the top three nations being China, the United States of America, and Iran. China emerges as the central hub for EMS research, responsible for 17.15% of the total publications. The United States follows closely with 442 articles, accounting for 11.92% of the contributions, while Iran ranks third in productivity, with 321 publications, representing 8.65% of the total research output.

TABLE 2. Number of publications produced from countries around the world

Countries/ Regions	Number of Articles	Countries/ Regions	Number of Articles
China	636	S. Arabia	157
USA	442	Pakistan	142
Iran	321	Japan	135
India	315	France	115
South Korea	261	Denmark	111
Italy	196	Germany	110
Spain	196	Taiwan	103
England	185	Egypt	82
Australia	182	Portugal	80
Canada	180	Malaysia	73

Table 3 shows the number of publications from the top ten journals containing research about EMS. The top journals contributing to research in the field of EMS are “ENERGIES,” leading with 355 publications, followed by “APPLIED ENERGY” with 189 publications and “IEEE ACCESS” with 178 publications. These journals have collectively played a pivotal role in the dissemination of research findings in EMS, with “ENERGIES” being the most prolific among them. The majority of the journals in the areas of (EMS concentrate their efforts on several key areas and topics, reflecting the interdisciplinary nature of EMS research.

Table 4 presents a list of researcher profiles along with their corresponding record counts and affiliations in the field of EMS. The researcher profiles signify individuals who have made significant contributions to EMS research and have authored or co-authored a notable number of publications in this area. Topping the list is Josep M. Guerrero, associated with the University of Cambridge, who has 52 publications, making him a leading figure in EMS research. In the second position, Mousa Marzband from Teesside University has authored 30 publications. Notably, Marzband’s affiliation with Teesside University, known for its research activities in energy management, highlights the institution’s role in fostering EMS research. In the third spot is Nadeem Javaid from COMSATS University Islamabad, with 25 publications to his credit. These authors, with their substantial publication records, play a pivotal role in advancing knowledge and innovation in EMS, and their affiliations reflect the collaborative efforts between academia and research institutions in this domain.

TABLE 3. Number of publications from the top ten journals containing research about Energy Management Systems published between 1973 and 2023

Publication Titles	Record Count	%
Energies	355	9.5
Applied Energy	189	5.0
IEEE Access	178	4.8
Energy	114	3.0
International Journal of Electrical Power Energy Systems	97	2.6
Sustainability	90	2.4
Energy Conversion and Management	87	2.3
Energy and Buildings	83	2.2
Electric Power Systems Research	68	1.8
Journal Of Energy Storage	63	1.7

TABLE 4. List of researcher profiles along with their corresponding record counts and affiliations in the field of Energy Management Systems (EMS)

Researcher Names	Number of Articles	Affiliation
Josep M. Guerrero	52	University of Cambridge
Mousa Marzband	30	Teesside University
Nadeem Javaid	25	COMSATS University Islamabad

continue ...

... cont.

Luis M. Fernández-Ramírez	25	Universidad de Cádiz
Pierluigi Siano	24	University of Salerno
Francisco Jurado	23	University of Jaén
Pablo García Triviño	23	Universidad de Cádiz
Hak-Man Kim	23	Incheon National University
Akhtar Hussain	23	University of Alberta
João P. S. Catalão	21	University of Porto

SCIENTOMETRIC RESULTS

Scientometric analysis was conducted to illuminate the intellectual terrain of EMS research, encompassing publications from 1973 to 2023. This comprehensive analysis involved a dual-map overlay and document co-citation analysis (DCA) to trace the development of this specialized research domain over time. The entire EMS research domain comprises a network of 1395 nodes, 2950 links and a density of 0.003, underscoring the extensive reach and interconnectedness of research within this field.

DUAL-MAP OVERLAY

A dual-map overlay analysis was employed to identify the most productive and highly cited disciplines and journals within the realm of EMS research (see Figure 2). The dual-map overlay revealed that articles centering on EMS predominantly found their place within the "Mathematics; Systems; Mathematical" discipline. On the other hand, the cited journals, which form the intellectual foundation of the research domain, were primarily clustered within the "Systems; Computing; Computer" (z score=5.51) and "Environmental; Toxicology; Nutrition" (z score=5.22) domains.

DOCUMENT CO-CITATION ANALYSIS

Document Co-citation Analysis provides a means to assess the frequency at which multiple documents have been co-cited by subsequent publications, thus yielding insights into the interconnectedness of knowledge. This network is shaped by both citing and cited documents downloaded directly from the WoS database. The assessment of the analysis's quality and the homogeneity of detected clusters was carried out using the modularity Q index and the average silhouette metric. For this DCA network, the modularity Q index is 0.8669, and the average silhouette metric is 0.9026, indicating that the network exhibits a high level of divisibility into distinct modules, and, on average, these modules display strong internal coherence. The DCA results were presented in terms of clustered analysis and individual analysis.

FIGURE 2. Dual map overlay on the impact of climate change on major aquatic species production in the world. Points represent literature, ellipses represent groups of subject matter, and directional lines represent the connection between subjects. Each unique discipline is represented by a different colour.

CLUSTER ANALYSIS

A total of 13 co-citation clusters emerged from the analysis (see Figure 3). These clusters were identified and ranked based on their sizes, with the largest cluster labeled as #0. The circle size within each cluster reflects the degree of influence of the publications, with larger circles indicating higher citation rates. The lines extending from each cluster represent the duration or lifetime of the cluster.

Notably, the size of each cluster corresponds to the number of publications it encompasses, with eleven out of the thirteen clusters comprising more than twenty publications, and cluster #0 being the most substantial in terms of the number of publications. Furthermore, the silhouette score for each cluster falls within a range from 0.818 to 0.999, signifying a commendable level of homogeneity among the publications within each cluster. Silhouette scores range from -1 to 1, with values exceeding 0 indicating a high degree of homogeneity.

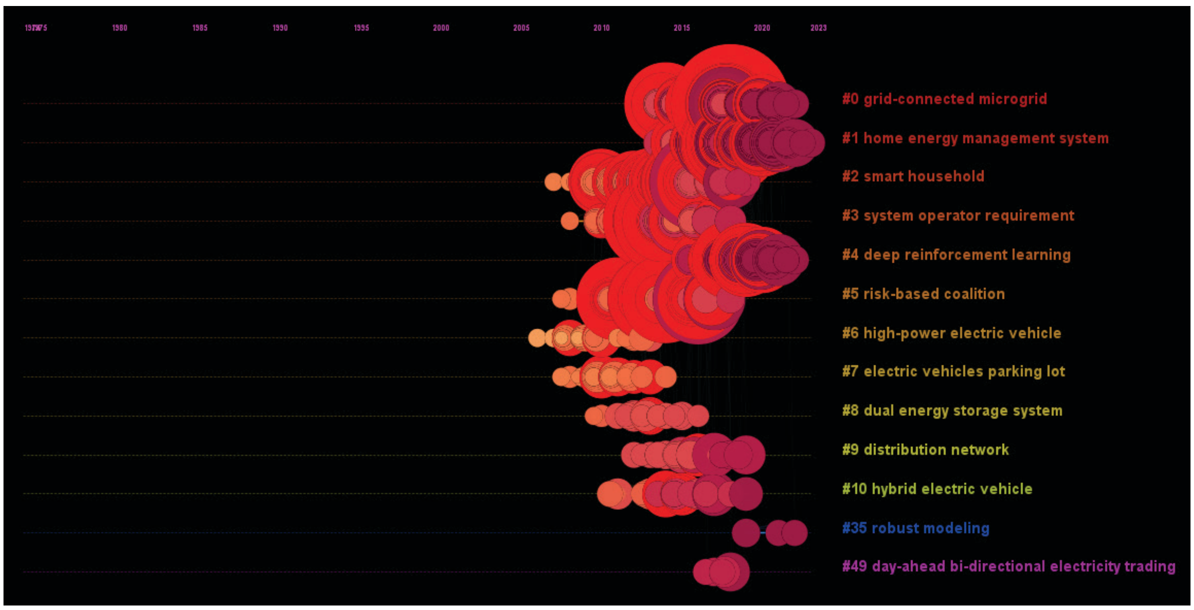

FIGURE 3. Summary of 13 identified document cluster lifetimes (solid lines). Cluster labels were generated from CiteSpace. Circle size corresponds to cluster size (i.e., number of publications).

Table 5 shows the 13 major clusters that emerged from DCA. The largest cluster in the network, cluster #0 (grid-connected microgrid), encompasses 165 nodes, representing a substantial 19.05% of the entire network. This cluster exhibits a silhouette score of 0.818, and the publications within it are predominantly dated to the year 2017, on average. Notably, the most cited articles in this cluster include works by Zia et al. (2018), Luna et al. (2017), and Arcos-Aviles et al. (2018).The second largest cluster, cluster #1 (home energy management system), comprises 164 nodes, equivalent to 18.94% of the network, and a silhouette score of 0.892.

On average, publications in this cluster were published around 2018. Prominently cited articles in this cluster include those authored by Shareef et al. (2018), Shafie-Khah et al. (2018), and Thomas et al. (2018). Cluster #2 (smart household) aggregates 132 nodes, representing 15.24% of the network, and exhibits a silhouette value of 0.899. The publications encompassed within this cluster exhibit a notable attribute, specifically, an average publication year that tends to center is 2013. Among the most cited articles in this cluster are contributions by Zhou et al. (2016), Beaudin & Zareipour (2015), and Anvari-Moghaddam et al. (2015).

INDIVIDUAL ANALYSIS

BURSTNESS

Table 6 presents the top ten references with a burst duration of more than 3 years in the context of EMS research. Citation bursts are indicative of periods when these references experienced a substantial increase in scholarly citations, reflecting heightened academic interest and impact. Palma-Behnke et al. (2013), Marzband et al. (2014a), and Mousa Marzband et al. (2013) exhibited robust citation bursts, with burst strengths ranging from 16.60 to 20.32, occurring between 2014 and 2018. These results underscore the temporal dynamics of scholarly attention and the lasting influence of these references within their respective research domains.

SIGMA

Table 7 provides insights into the top ten references with the highest sigma values within the realm of Energy Management Systems (EMS) research. Sigma is a metric that assesses scientific novelty by combining centrality and burstness. It measures the degree of originality and the impact of a publication in a given field. Chaouachi et al. (2013) have a high sigma value of 2.58 and a centrality of 0.09, indicating a substantial level of scientific novelty. Next, Palma-Behnke et al. (2013) closely follow with a sigma of 2.53 and centrality of 0.05, signifying its notable originality and impact. The third article with high sigma is Zhou et al. (2016) with a sigma value of 1.49. These references have made substantial contributions characterized by their originality and influence, thus warranting special attention in EMS literature.

TABLE 5. The 13 major clusters that emerged from Document Co-citation Analysis. Size represents the number of publications in a cluster, and silhouette score indicates levels of homogeneity. Labels were derived from log likelihood ratios (LLR).

Cluster ID	Size	%	Silhouette	Label (LLR)	Average Year
0	165	19.05	0.818	grid-connected microgrid	2017
1	164	18.94	0.892	home energy management system	2018
2	132	15.24	0.899	smart household	2013
3	101	11.66	0.891	system operator requirement	2013
4	73	8.43	0.963	deep reinforcement learning	2019
5	53	6.12	0.962	risk-based coalition	2012
6	45	5.20	0.981	high-power electric vehicle	2009
7	38	4.39	0.911	electric vehicles parking lot	2010
8	33	3.81	0.964	dual energy storage system	2013
9	28	3.23	0.943	distribution network	2015
10	24	2.77	0.984	hybrid electric vehicle	2015
35	5	0.58	0.999	robust modelling	2021
49	5	0.58	0.998	day-ahead bi-directional electricity trading	2017

TABLE 6. Top ten publications with the strongest citation bursts between 1973 and 2023

References	Burst	Burst Begin	Burst End
Palma-Behnke et al. (2013)	20.32	2014	2018
Marzband et al. (2014a)	17.34	2014	2018
Mousa Marzband et al. (2013)	16.60	2014	2018
Marzband et al. (2014b)	14.50	2015	2019
Parisio et al. (2014)	12.71	2015	2019
Beaudin & Zareipour, (2015)	11.00	2016	2020
Chaouachi et al. (2013)	10.67	2014	2018
Jiang et al. (2013)	10.30	2014	2018
Shareef et al. 2018)	8.58	2019	2023
Luna et al. (2017)	7.03	2019	2023

DISCUSSION

This study is aimed to synthesize EMS research published between 1976 and 2023 using the WoS database and the scientometric tool, CiteSpace. This research seeks to answer several key questions: (i) What are the overall publication trends in terms of output? (ii) What are the central topics/clusters? and (iii) What are the most influential publications in these domains? In the following section, a thorough examination of the results will be provided, offering in-depth analysis and a comprehensive exploration of the findings.

TABLE 7. Document Co-citation scores for the top ten articles related to research on Energy Management Systems

References	Centrality	Sigma
Chaouachi et. al. (2013)	0.09	2.58
Palma-Behnke et. al. (2013)	0.05	2.53
Zhou et. al. (2016)	0.04	1.49
Olivares et. al. (2014) (a)	0.04	1.46
Jiang et. al. (2013)	0.04	1.45
Marzband et. al. (2013)	0.04	1.44
Shi et. al. (2015)	0.04	1.44
Chen et. al. (2012)	0.06	1.43
Parisio et. al. (2014)	0.04	1.43
Paterakis et. al. (2015)	0.04	1.42

(i) What are the overall publication trends in terms of output?

A comprehensive analysis was conducted, incorporating descriptive analysis and dual-map analysis, to provide a holistic view of publication trends in EMS research. The descriptive analysis encompassed an evaluation of the number of publications, involved countries or regions, contributing journals and authors. This examination revealed 3,708 publications with h-index of 130.

These publications have garnered 98,600 citations and 26.59 citations per article. Notably, this body of research has exhibited a consistent upward trajectory spanning from 1973 to 2023, illustrating the enduring relevance and growth of the EMS domain. Furthermore, the research areas have the participation of 106 countries, with China, the United States of America, and Iran emerging as the primary contributors.

This surge in research output can be attributed to several factors. First and foremost, the escalating concerns about climate change and the need for sustainable energy solutions have fueled the demand for EMS research. Governments, organizations, and researchers worldwide have recognized the urgency of addressing energy efficiency and environmental impact. As a result, substantial research funding and academic interest have been directed toward EMS. Furthermore, technological advancements, particularly in areas like smart grids and renewable energy integration, have opened up new avenues for exploration. Researchers have been quick to capitalize on these opportunities, resulting in the exponential growth of publications.

The dominant role played by China, the United States, and Iran in EMS research can be linked to their specific energy needs and national priorities. China, as a rapidly developing nation with a significant population, faces both surging energy demands and pressing environmental challenges. Consequently, China has a vested interest in advancing research in efficient energy management. The United States, a global leader in technology and research, naturally occupies a central position in shaping the EMS landscape. Iran, due to its geographical location and energy requirements, is focusing on harnessing renewable energy sources and enhancing energy efficiency. These national priorities align with the global call for sustainable energy solutions, further underscoring the prominence of EMS research in these countries.

The key journals driving EMS research, such as "ENERGIES," "APPLIED ENERGY," and "IEEE ACCESS," have contributed significantly to the field's development. These journals have fostered an environment that emphasizes EMS topics and attracted contributions from researchers worldwide. As a result, they have become instrumental in advancing the field. The analysis highlighted Josep M. Guerrero from the University of Cambridge as a preeminent figure in the field with 52 publications, Mousa Marzband with 30 publications and Nadeem Javaid in the third position with 25 publications. These key researchers, through their substantial publication records, significantly contribute to the advancement of knowledge and innovation in EMS.

The dual-map overlay revealed that articles centring on EMS predominantly found their place within the "Mathematics; Systems; Mathematical" discipline and there were few publications in other disciplines. On the other hand, the cited journals, which form the intellectual foundation of the research domain, were primarily clustered within the "Systems; Computing; Computer" (z score=5.51) and "Environmental; Toxicology; Nutrition" (z score=5.22) domains. This outcome suggested that a significant proportion of EMS articles were deeply entrenched in specific sub-domains of pure science and less so in the social sciences. However, there were indications of collaborative efforts from other disciplines, as evidenced by the connecting lines between cited and citing articles in other domains. This suggests that EMS is gradually making inroads into more interdisciplinary research endeavours. To further advance EMS research, a suggestion is made to maintain a focus on international scientific research exchanges and collaboration.

(ii) What are the central topics or clusters?

To answer the second research question, a document cluster analysis has been conducted and yielded a total of 13 co-citation clusters. According to the results, the top three dominant research topics and directions were "grid-connected microgrid", "home energy management system" and "smart household". The robust silhouette values of these top clusters indicate a high level of internal consistency within each of them.

In cluster #0 "grid-connected microgrid", the most frequently cited articles are authored by Zia et al. (2018), Luna et al. (2017), and Arcos-Aviles et al. (2018). The average year of articles in this cluster was published in 2017. The majority of the articles in the cluster revolve around the application of EMS within microgrid environments. This cluster predominantly focus on the integration of distributed energy resources into microgrids, with an overarching aim of enhancing energy efficiency, reliability, and sustainability. Zia et al. (2018) underscore the vital role of EMS in microgrids, offering a comparative analysis of decision-making strategies and methods for addressing uncertainty. It also delves into the relevance of communication technologies in the successful implementation of these systems. Luna et al. (2017) concentrate on the modeling and design of a modular energy management system tailored for grid-connected microgrids. The core emphasis lies in optimizing the scheduling of distributed energy resources to curtail operational costs and augment self-consumption. Arcos-Aviles et al. (2018) introduce a low-complexity fuzzy logic controller seamlessly integrated within an EMS designed for residential microgrids. The primary objective here is to minimize fluctuations in grid power profiles while concurrently maintaining prescribed battery state-of-charge limits. This strategy highlights the significance of real-time control predicated on variables such as energy rate-of-change and battery state. Collectively, articles in this cluster encapsulate the challenges and intricacies associated with managing distributed energy resources within microgrids, through the ingenious application of energy management systems. It shared emphasis on the critical nature of informed decision-making strategies, scheduling optimization, and effective control mechanisms in the pursuit of efficient and sustainable microgrid operations, particularly in the context of renewable energy integration.

Cluster #1 (home energy management system) on the other hand, focuses on home energy management systems (HEMS) and demand response (DR), with notable citations from Shareef et al. (2018), Shafie-Khah et al. (2018), and Thomas et al. (2018). The average year of articles in this cluster was published in 2018. Shareef et al. (2018) emphasize the significance of HEMS within the context of surging electricity demands and smart grids. It delineates how HEMS, in conjunction with DR tools, optimizes residential energy consumption, considering factors like energy costs, environmental impact, load profiles, and consumer comfort. Shafie-Khah et al. (2018) tackle the pragmatic challenges confronting HEM systems, stemming from uncertainties linked to renewable energies, consumer behaviors, and appliance constraints. The study underscores the imperative of ensuring customer satisfaction and mitigating "response fatigue" over the long term. In parallel, Thomas et al. (2018) introduce a mixed-integer linear programming (MILP) framework-based model that evaluates EMS within a building. It incorporates bidirectional energy trading of an electric vehicle (EV) fleet, addresses the influence of photovoltaic (PV) uncertainties, and explores the effects of different prioritization factors. Collectively, articles in this cluster underscore the increasing importance of energy management systems, the integral role of demand response, and the complexities posed by renewable energy integration within the dynamic landscape of smart grids. It also underscores the growing demand for innovative optimization techniques and the active participation of end-users in energy management and demand response initiatives.

Finally, in Cluster #2, the central theme revolves around the relationship between HEMS and smart households. Notably cited articles within this cluster include contributions by Zhou et al. (2016), Beaudin & Zareipour (2015), and Anvari-Moghaddam et al. (2015). The average year of articles in this cluster was published in 2013. Zhou et al. (2016) introduce the concept of the smart household grid and the transition toward autonomous and responsive energy management. The focus lies on HEMS, which plays a pivotal role in enhancing efficiency, economic viability, and energy conservation in smart homes. This includes an in-depth exploration of architectural aspects, functional modules, renewable energy integration, and scheduling of home appliances. Beaudin & Zareipour (2015) tackle the surging electricity demand and the emergence of smart grids by emphasizing the role of smart houses as a solution within demand markets. This research delves into the creation of optimal consumption patterns, taking into account various factors such as energy costs, environmental considerations, load profiles, and consumer comfort. Anvari-Moghaddam et al. (2015) further deepen our understanding of optimal energy management in residential buildings. It presents a comprehensive mixed integer nonlinear programming model with multiple objectives. This model seeks to strike a balance between minimizing energy consumption costs, enhancing user convenience, and maintaining a comfortable living environment, thus representing a holistic approach to smart home energy management. The common thread across these articles in Cluster #2 is the shared pursuit of efficient and sustainable energy management within residential contexts. This drive is strongly motivated by the emergence of smart grids and the integration of renewable energy sources. Together, these articles encapsulate the multifaceted landscape of EMS and their evolving role in shaping the energy consumption patterns of smart homes.

Considering the research clusters discussed, these research directions align with the evolving energy landscape, which highlights the importance of EMS. Future research can concentrate on the development of personalized and user-centric EMS, leveraging artificial intelligence and the IoT, while studying user behavior and its impact on energy consumption within smart households. These research avenues align with the evolving energy landscape, emphasizing sustainability, reliability, and user-centric approaches, with the potential to drive significant advancements in energy management systems, microgrid resilience, consumer engagement, and the integration of emerging technologies.

(iii) What are the most influential publications in these domains?

To address our third research question, we conducted a DCA of the articles. This analysis yielded three key metrics: burstness, centrality, and sigma. Burstness revealed surges in citations for individual articles, signifying the extent of citations garnered during specific years. Centrality scores pinpointed the most influential articles within the research domain, with higher scores denoting increased influence. Sigma synthesized both centrality and burstness, offering an assessment of the scientific novelty of the articles.

The document burst analysis revealed a trend of the emergence of new research topics and the progressive replacement of earlier burst publications by more recent ones. The earliest burst start at 2013, the dominant themes revolved around the development of novel energy management systems (EMS) and their application in microgrids, particularly in optimizing the scheduling of distributed energy resources, cost-efficiency, and environmental considerations (Palma-Behnke et al. 2013; Mousa Marzband et al. 2013; Marzband et al.2014a). By 2014, burst value has shown there was a surge in interest in optimization techniques for distributed generation within microgrids, emphasizing gravitational search algorithms and predictive control approaches (Marzband et al. 2014b; Parisio et al. 2014). Concurrently, the article that burst in 2014 also saw a focus on intelligent energy management, employing artificial intelligence and fuzzy logic for microgrid optimization (Chaouachi et al. 2013; Jiang et al. 2013). In 2015, there was a transition towards home energy management systems (HEMS) and demand response (DR), exploring consumer comfort and efficient operation schedules (Beaudin& Zareipour, 2015). Finally, the burst themes from 2019 to 2023 shifted towards the application of HEMS, demand response, and artificial intelligence in improving home energy consumption and load scheduling (Luna et al. 2017; Shareef et al.2018). These themes indicate a progression from microgrid-centric research to a stronger emphasis on residential energy management and smart grid integration, in alignment with evolving technological capabilities and consumer demands.

The most influential publications within EMS research areas are Chaouachi et al. (2013) with a Sigma of 2.58. It explores the integration of artificial intelligence techniques and multi-objective optimization in microgrid energy management, emphasizing cost minimization and reduced environmental impact. Palma-Behnke et al. (2013), with a Sigma of 2.53, present an innovative approach to renewable-based microgrid EMS, incorporating forecasting models and demand-side management, indicating a practical economic sense. Zhou et al. (2016), with a Sigma of 1.49, offer insights into the shift towards autonomous responsive demand in the smart grid era and emphasizes the role of smart houses and HEMS in improving efficiency, economics, and energy conservation. These influential publications lay the foundation for future research in the domain by highlighting the significance of advanced technologies, optimization techniques, and the transition toward responsive, sustainable energy management systems in both microgrid and residential contexts. These influential publications collectively contribute to guiding future research by showcasing advanced techniques, adaptability, and comprehensive approaches to EMS in both microgrids and residential settings, in alignment with evolving energy paradigms and consumer requirements.

CONCLUSION

This study provides a comprehensive overview of current research on Energy Management Systems (EMS), highlighting significant gaps and future directions. While the reliance on the Web of Science (WoS) database may introduce biases, WoS ensures high publication standards and broad coverage. Future research could compare WoS with other databases to identify any missing information. CiteSpace software was utilized in place of manual data collection to conduct the analysis, potentially resulting in the inclusion of some irrelevant subjects. However, this approach makes the analysis reproducible. Striking the right balance between strict criteria and excluding specific studies is challenging. Future research could improve precision by refining keyword searches or manual data reviews. Moving forward, advanced artificial intelligence and machine learning techniques should be explored to enhance EMS performance, particularly in microgrids and home energy management systems (HEMS). Research should also focus on balancing energy supply and demand, ensuring environmental sustainability, and implementing EMS solutions in real-world scenarios for scalability and economic viability. Finally, policy, regulatory, and cybersecurity considerations must be addressed to support effective adoption of EMS technologies.

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DECLARATION OF COMPETING INTEREST

None.

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