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Battery energy storage performance in microgrids: A scientific mapping perspective

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Abstract

Microgrids integrate various renewable resources, such as photovoltaic and wind energy, and battery energy storage systems. The latter is an important component of a modern energy system, as it allows the seamless integration of renewable energy sources in the grid. The research here presented aimed to develop an integrated review using a systematic and bibliometric approach to evaluate the performance and challenges in applying battery energy storage systems in microgrids. Search protocols based on a literature review were used; this included thematic visualization and performance analysis using the scientific mapping software SciMAT (Science Mapping Analysis Software Tool). The results show that optimization methods in battery energy storage systems are important for this research field. In research works, they are interested in applying methods to reduce costs; this includes considering the state of charge, the degradation rate, and battery life. Developing an optimal battery energy storage system must consider various factors including reliability, battery technology, power quality, frequency variations, and environmental conditions. Economic factors are the most common challenges for developing a battery energy storage system, as researchers have focused on cost–benefit analysis.

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Keywords: Battery energy storage system; Lithium-ion battery; Lead-acid battery; Literature review; State of change

1. Introduction

With a global shortage in fossil fuels and growing concern for the environment, the interest and advances in renewable energy have gained rapid momentum in recent decades [1]. Currently, there is substantial attention on

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microgrids (MGs) due to their ability to increase the reliability and controllability of power systems. MGs are a set of decentralized and intelligent energy distribution networks, which possess specific characteristics critical to the evolution of energy systems [2]. There exist several definitions of microgrid in the scientific literature [3–6]. As a reference, we can consider the definition given by the Consortium for Electric Reliability Technology Solutions (CERTS) [5], where a microgrid is: "a cluster of loads and micro-sources operating as a single controllable system that provides both power and heat to its local area". On the other hand, there is also no convention on the size classification of microgrids. Generally, microgrids are low or mid-voltage internal distribution networks installed in small areas (districts, industrial areas, university campuses, etc.), but also buildings and industrial plants can be considered as microgrids (usually known as nanogrids) [5]. According to the existing literature [3,7–9], typical simple microgrids (one type of energy source) connected to the main grid have a rated power capacity in the range of 0.05–2 MW, a corporative microgrid is in the range between 0.1 and 5 MW, a microgrid of feeding area, is in the range of 5 to 20 MW and a substation microgrid is in the range of 10 to 20 MW. Isolated microgrids can be of any size depending on the power loads. In this sense, MGs are made up of an interconnected group of distributed energy resources (DER), including grouping battery energy storage systems (BESS) and loads. The BESS is fundamental to the operation of MGs as they can compensate for fluctuations in energy generation to meet demand fluctuations [10].

BESS's have been attracting considerable investment and creating a market for MGs. Alongside technological advances in power electronics, BESSs are becoming financially and technologically viable. In the same way, researchers are interested in proposing optimization models to identify the best possible traditional BESS in terms of cost-effectiveness, high usable life, reliability, and least environmental impact. For example, a study [11] has examined the storage-as-a-service business model in the marketplace, in which two main business model archetypes were identified. Projects were distinguished based on whether the end-user owns their BESS, and when the BESS is offered as a service by a third party.

Another review focused on control strategies to smooth wind energy production using BESS [12,13]. The authors classified control technologies into three main categories: wind power filtering, BESS loading/unloading dispatch, and optimization using wind speed predictions. Thus, storage devices based on battery technologies can be utilized in various types of applications based on the charge and discharge requirements of MGs. Similarly, a BESS comparison report was prepared to describe longevity, cycles, efficiency, and installation cost. For example, a study [14] has discussed approaches based on multi-criteria decision-making in BESS.

As such, batteries have been the pioneering energy storage technology; in the past decade, many studies have researched the types, applications, characteristics, operational optimization, and programming of batteries, particularly in MGs [15]. A performance assessment of challenges associated with different BESS technologies in MGs is required to provide a brief discussion of this review. The main objective of this study is to develop an integrated analysis using a systematic literature review (SLR) and bibliometric analysis.

2. Methodology

Integrated analysis was carried out using an SLR and scientific mapping based on bibliometric analysis to achieve the stated objectives [16–19]. Systematic reviews answer specific questions objectively and in an unbiased manner, using methods to select studies, data extraction, and analyze results [20]. Thus, they are able to establish a protocol that describes the objectives of the review and inclusion and exclusion criteria [21]. The main phases used to obtain results include development, execution, and compilation protocols [22]. Similarly, scientific mapping shows the structural characteristics of scientific research and the architecture of the academic field [23].

2.1. A systematic review of the literature

The SLR search protocol was developed by considering two databases for analysis: the Web of Science (WoS), and Scopus databases [24]. As such, the following Boolean search equation was developed: (("lead-acid" OR "lead-acid" OR "LA") OR ("nickel-cadmium" OR "nickel-cadmium" OR "Ni-Cd") OR ("lithium-ion" OR "lithium-ion" OR "Li-ion") OR ("Redox flow" OR "Redox-flow") OR ("Sodium-Sulfur" OR "Sodium Sulfur" OR "Na-S") OR ("Zinc-Bromine" OR "Zinc Bromine" OR "Zn-Br") OR ("Sodium-Nickel-Chloride" OR "Sodium Nickel Chloride" OR "ZEBRA")) AND (batteries* OR battery*) AND ("Microgrid*" OR "micro-grid*"). Papers from 2016 to July 2021 were selected due to the significant increase in research over this period.

The search results were restricted to research articles, and conferences, books, and chapters were excluded. A review process was carried out using the execution protocol to identify articles and all duplicates were eliminated. Exclusion (i) and inclusion (ii) criteria were established, consisting of two steps [25]: In this way, the initial analysis was based on the title, abstract, and keywords, consideration of the following exclusion criteria: is the article on BESS applicable to MGs to microgrids? During (ii), the inclusion criteria of the study were used, which involved reading and analyzing articles to identify answers to research questions.

2.2. Bibliometric analysis

The results were presented based on the determination of the bibliometric analysis using the scientific mapping method with the SciMAT software (Science Mapping Analysis Software Tool) [26–28]. Scientific mapping applies algorithm-based evaluation, providing an unbiased view of the research topic. As such, this method uses a quantitative approach to analyze published documents and applies statistical methods to establish an objective perspective [16,26]. The most common methods of bibliometric analysis are citation-based analysis, co-authorship analysis, and keyword co-occurrence analysis [29]. In this sense, the keyword co-occurrence analysis was used to identify and build a thematic network, and trends in the topics were identified [16,26]. The identification of themed trends was carried out using SciMAT, which facilitated the visualization of themes in a strategic diagram and the representation of thematic networks [30].

Each theme was characterized in two dimensions: centrality and density [30]. Centrality measures the degree of interaction of a network with other thematic networks in an evaluated field, showing the strength of external links, and is defined by Equation $c = 10\sum e_{uv}$; where u is an element (keyword) belonging to the theme; and v is an element (keyword) belonging to other themes. Density assesses the internal strength of the thematic network; this is the strength of the relationship between the number of related keywords generated by the thematic network. Density was defined by Equation $d = 100(\sum e_{eij}/n)$. where i and j are the elements (keywords) belonging to the theme; and n is the number of elements (keywords) in the theme. Fig. 1 presents a visualization of the strategy diagram.

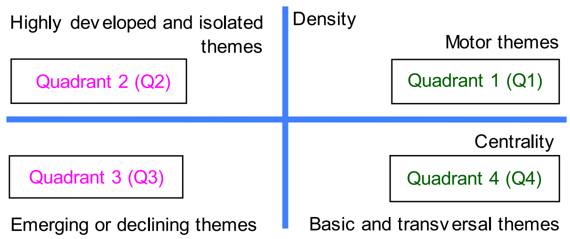

Fig. 1. Structure of the strategic diagram.

The strategic diagram of the topic was divided into four quadrants (Fig. 1), representing four different types of topics: motor, basic, specialized, and emerging. The basic themes (Q4) were important for the research area, although they were not fully developed based on their internal links in the thematic network. The specialized topics (Q2) comprise topics isolated from other topics, although they are well-developed internally because of their high density. Therefore, specialized topics are developed in-house, making a limited contribution to the research area. Finally, topics with poorly developed internal and external networks represent emerging topics (Q3) in a certain research area [31]. The equivalence index is considered an indicator of the frequency of normalized co-occurrence. The higher the percentage of documents in which two keywords are shown together based on the totality of documents in which they are shown, the thicker the line between spheres in the thematic network [16,32].

3. Results and discussion

3.1. Final database

251 research articles were identified in journals indexed in both databases using the search equation, and 56 duplicate articles were identified. There were 70 documents eliminated by analyzing the exclusion criteria; 125 articles were eligible for the next stage. This meant a total of 63 articles were selected through the analysis of the inclusion criteria, all of which were within 2016 to 2021 (June) period, as shown in Fig. 2.

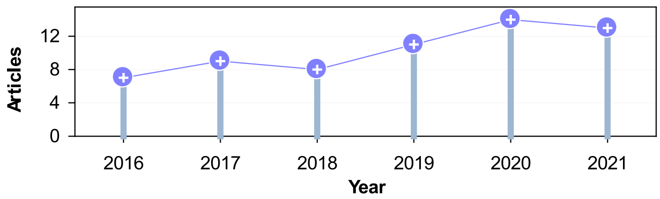

Fig. 2. Final base of articles used by years.

3.2. Overlay graph and evolution map

Fig. 3 shows the overlay graph (Fig. 3a) and the thematic evolution map (Fig. 3b). In Fig. 3a, the number of new and transition keywords was high, while the number of shared keywords was at a relatively high percentage (50% to 65%) for successive periods. As keywords reappeared with the same or greater force in subsequent periods was indicative of the progressive consolidation occurring in this field of research. Fig. 3b shows the thematic evolution of the BESS through an analysis of the origins and the interrelationships of the themes. Based on the number of documents, energy storage systems and lead-acid batteries were topics with the highest number of published documents.

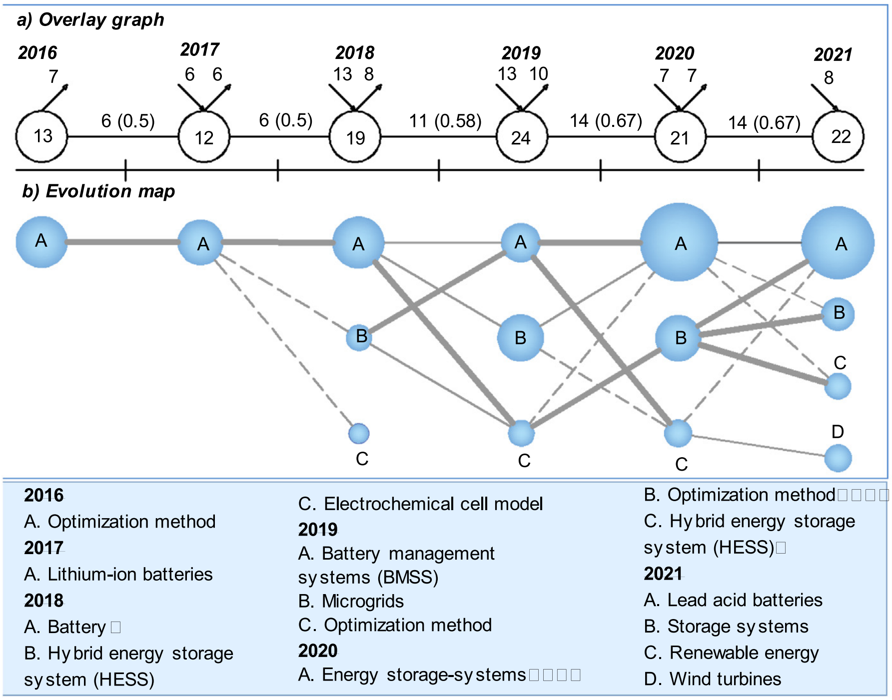

Fig. 3. Overlay graph and thematic evolution.

3.3. Strategic diagram and thematic network

In 2016, based on Fig. 3b, the optimization methods were the single most representative topic for the period. This issue is considered important for the BESS, as it is presented as a motor issue (Q1) according to Fig. 3a. The thematic network shows that the optimization methods were closely related to electric vehicles, lead-acid batteries, levelized cost of energy (LCOE), Lithium-Ion Batteries (LIBs), storage systems, the Battery Management Systems (BMSS), and wind turbines. According to the articles reviewed, genetic algorithms (GAs) were one of the optimization techniques used in this period. As such, the application of storage technologies in autonomous systems and connection to the network was very relevant for the integration of renewable energy sources with a focus on sustainability.

In 2017, LIBs were the most representative topic, being in the first quadrant (Q1). As such, LIBs were considered a motor theme for BESS based on their high density and centrality. LIBs have featured prominently among various rechargeable energy storage systems [33] because they have higher gravimetric and volumetric energy densities compared to other types of batteries (e.g., lead-acid batteries). Furthermore, unlike nickel-cadmium (Ni-Cd) batteries, LIBs do not have a "memory effect". The "memory effect" is the reduction in a Ni-Cd battery capacity, due to incomplete charge and discharge cycles [34]. Therefore, there are two negative consequences: the usable capacity of the battery is reduced, and the correlation between voltage and state of charge is shifted (voltage cannot be reliably determined). The topic of LIBs in the thematic network relates to electric vehicles, MG, net income, renewable energy, energy storage systems (ESS), wind turbines, DC/DC converters, and BMSS.

In 2018, three more well-known topics are presented: battery technology, hybrid energy storage systems (HESS), and electrochemical cell models. The first two were in Q1 of the strategy map, representing the most relevant and important topics within the research field. Electrochemical cell models were found in the third quadrant (Q3) and were considered an emerging or declining topic in the research field. BESS was considered one of the most efficient methods to obtain a reliable power supply by incorporating renewable energy resources. To date, lead-acid batteries have been the most commonly used electrochemical energy storage technology for grid-based applications. However, many other technologies are also being used, such as LIBs, sodium-sulfur, and flow batteries. The HESS was related to the issues associated with distributed energy resources, electric vehicles, energy sources, PV systems, and operating strategies.

In 2019 three main themes were presented: the BMSS, MGs, and optimization methods. The global panorama in the evolution of electricity distribution and use has created a priority area of interest, as is the case for ESSs. A key element is the ability to monitor, control, and optimize the performance of one or more battery modules within a storage system. The BMSS topic was identified in Q1 of the strategy map, which is considered important in the field studied. The equivalence index shows that the BMSS is closely linked to the ESS, LIBs, power management strategies, HESS, and the maximum power point tracker (MPPT). MGs are in Q1 of the thematic network, which is considered an important topic in this field of research due to its high centrality and density. MGs are also related through a thematic network with distributed energy resources, distributed power supplies, energy resources, local outliers, and solar photovoltaic (PV) energy.

In 2020 three themes were presented in the strategic diagram of the research field; these themes consisted of ESSs, that were in Q1 and included relevant topics in the research field. Similarly, the HESS was presented in the second quadrant (Q2) and was considered a specialized topic; therefore, they were isolated topics within the strategic network. Finally, optimization methods were presented as basic or cross-cutting themes that were considered important and growing within the BESS. The ESS was related to electric vehicles, energy management systems, LIBs, vanadium redox flow batteries, MGs, and power conditioning systems. As such, during this period, research reports were focused on the ESS to increase energy resilience in PV installations [35]. Different models of LIBs for the design and monitoring of MGs have also been researched [36]; two analytical and electrical modeling approaches were developed, to represent the state of charge (SoC) and state of Health (SoH) indicators.

In 2021, the strategic map presents four research topics: lead-acid batteries, renewable energy, ESSs, and wind turbines. One of the important issues is in Q1 and corresponds to lead-acid batteries; this, in turn, contains or is related to other topics such as depth of discharge (DoD), LIBs, MGs, nanogrids, and PV systems according to Fig. 4 of the thematic network. The incorporation of ESS plays a fundamental role in maintaining economic importance and mitigating the technical responsibilities associated with producing renewable energy with fluctuating characteristics. During this period, ESS and wind turbines were in Q1 and the Q4 quadrant, respectively; they represented the motor themes and basic or transversal of the specialty, in that order. As such, they were related (Fig. 4) to electric vehicles, LCOE, HESS, battery management systems (BMS), and renewable energy resources.

The bibliometric analysis shows the importance of battery storage technologies based on LIBs, lead-acid batteries and Vanadium Redox flow batteries, as shown in Figs. 3 and 4. LIBs have characteristics of high-energy and power density, well suited for transport and stationary applications [37]. While lead-acid batteries are characterized by moderate input and output efficiency, as well as low cost [38], and are suitable for stationary applications [37]. On the other hand, Vanadium Redox flow batteries are one of the emerging energy storage technologies that are being

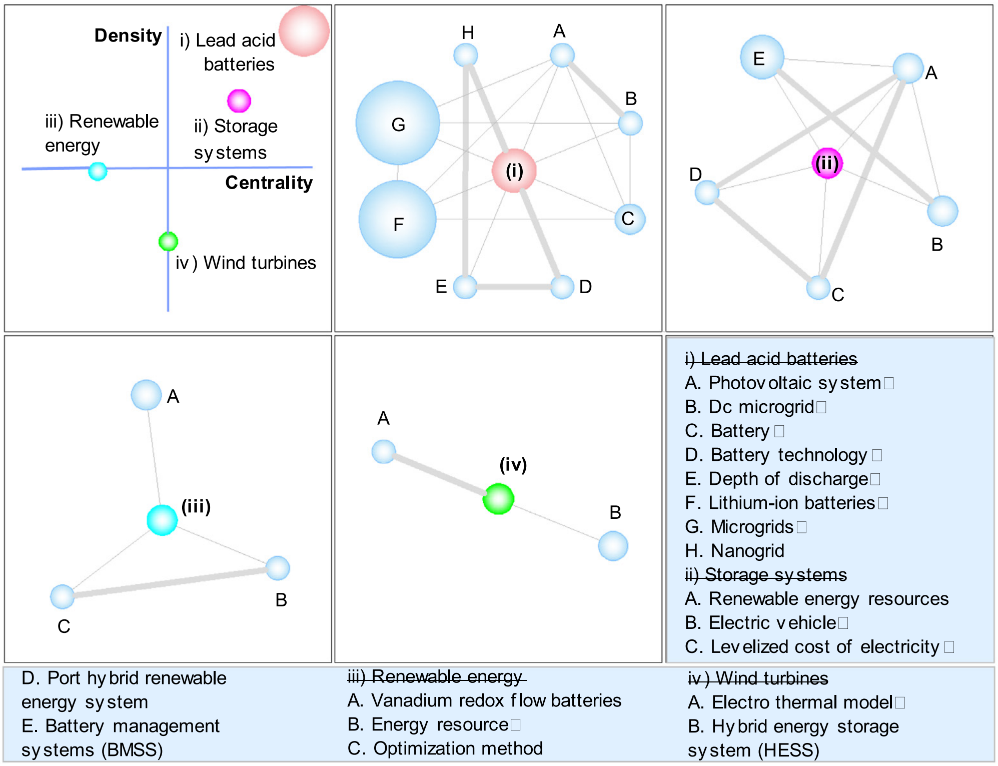

Fig. 4. Strategic map and thematic networks of 2021.

developed with the aim of storing renewable energy more efficiently. In the case of Sodium nickel chloride batteries, they have a round trip efficiency of between 80 and 90% (stationary storage). While Nickel-metal hybrid batteries and Sodium-sulfur batteries are more favorable in the case of high current rate discharges [39]. Likewise, Nickel-cadmium batteries contributions to stationary energy storage applications with a higher specific power. However, they have a high self-discharge rate. Table 1 shows the technical characteristics of the storage technologies used in MGs. The specific energy is shown in Wh/kg, the specific power in W/kg, the efficiency in %, the service life in years, the Self-discharge rate in %, and use according to the utilization of batteries (Front of the Meter — FTM or Behind the Meter — BTM).

Table 1. Technical characteristics of the storage technologies used in MGs.

Technology	Specific energy (Wh/kg)	Specific power (W/kg)	Efficiency (%)	Service life (years)	Self-discharge rate (%)	Use	Source
Lithium-ion batteries	75–250	150–315	85–95	5–15	0.1–0.3	FTM/BTM	[40,41]
Lead acid batteries	30–50	75–300	70–80	5–15	0.1–0.3	FTM/BTM	[42,43]
Redox flow batteries vanadium	10 a 35	100–166	65–85	15	~0	FTM	[44]
Sodium Sulfur batteries	150–240	150–230	80–90	15	~0	FTM	[40,45]
Sodium nickel chloride batteries	100–120	150–200	80–90	10–15	Moderate	FTM	[38,46]
Nickel metal hybrid batteries	70–100	200–300	70	5–10	High	–	[38,47]
Nickel–cadmium batteries	50–75	150–300	70	10–20	0.03–0.6	–	[47,48]
Polysulphide bromine redox flow battery	10 a 35	100–166	65–85	15	~0	–	[47,49]
Zinc bromine redox flow battery	70	100–166	65–90	15	~0	–	[50]

Finally, flow batteries represent another way of storing stationary energy. In addition to Vanadium Redox flow batteries, there are Polysulphide bromine redox flow batteries and Zinc bromine redox flow batteries. These types of batteries are referenced as an advantage in stationary storage applications because they have low self-discharge, long life, and fast response characteristics (Table 1); however, it is still an emerging technology. According to [44], the electrolytes that make up a battery of this type react with each other to provide electrical potential. Initially, some vanadium compounds were used for use in electrolytes, such as vanadium trichloride (VCl_3), vanadium pentoxide (V_2O_5), and vanadium sulfate ($VOSO_4$). Each of them was used with hydrochloric acid (HCl), sodium hydroxide (NaOH) and sulfuric acid (H_2SO_4). Currently, V_2O_5 is used when seeking to reduce the cost of electrolytes, and $VOSO_4$ when is desired to vary the concentration of vanadium.

3.4. Future trends

There are different battery types that vary by the shape of the electrode and the electrolyte material, in order to be suitable for a specific range of applications. The most important types of batteries used for power grids are lead-acid batteries, as shown in Table 2, due to their high density and centrality. Similarly, LIBs are considered important because of their frequency of use in research reports. In addition to the redox flow batteries that are in third place as the most important for MG applications, nickel-cadmium batteries are also used less frequently.

Table 2. Detection of research topics and performance analysis by period.
Source: Own elaboration.

Period	Cluster	Centrality	Density	Quadrant
2016	Optimization method	30	71.53	1
2017	Lithium-ion batteries	23.83	49.17	2
2018	Battery	55.56	139.42	1
	Hybrid energy storage system (HESS)	48.17	127.78	1
	Electrochemical cell model	4.29	100	3
2019	Battery management systems (BMSS)	59.11	124.07	1
	Microgrids	64.38	59.26	1
	Optimization method	46.73	27.08	3
2020	Energy storage systems	41.87	81.54	1
	Hybrid energy storage system (HESS)	6.2	56.25	2
	Optimization method	40.59	37.5	4
2021	Lead-acid batteries	27.75	93.4	1
	Storage systems	23.03	75	1
	Renewable energy	7.5	56.25	2
	Wind turbines	14.72	25	4

Table 2 lists the most important issues related to the application of BESS to determine their performance within the research field. During the first period, the optimization methods were the most representative topic related to the BESS as it was presented as a motor topic. Optimization methods have been used in storage systems; mainly in lead-acid batteries and LIBs, and as a result, researchers have focused on optimizing LCOE. The LCOE is used extensively by researchers, investors, project managers, and policymakers. Similarly, energy optimization using BMSS is a thematic inclination by researchers. This is because the BMSS is key to the operation of an electrical system and is considered one of the basic units in a BESS. The BMSS detects and controls external and internal events, protecting the battery pack and associated system.

The BMSS attempts to secure and provide the most accurate battery condition estimates and predictions; this facilitates an extension of the battery life and better use of energy. In Table 2, the analysis of BMSS performance shows a high centrality and density; an indicator of the scientific need to fill these gaps. In addition, one of the fundamental objectives of the BMSS is to increase its robustness and reliability, allowing improvements in BESSs without a significant decrease in the functionality or performance of the MG energy supply. At present, battery systems generally do not provide facilities that allow the continuation of system operation after cells within a BESS have failed, as they do not have mechanisms to carry out isolation automatically [51]. Therefore, it is important to present studies on improving the reliability of MGs, ensuring the continuous supply of electrical energy to end-users. Various methods to size HESS capacity have been reported in the literature, such as objective functions to determine energy storage capacity. Shelf life is one of the important factors and an important objective is the size of the BESS. It is expected that in future research, the capacity of HESS in MGs may be determined by considering parameters such as SoC and DoD. Similarly, SoC, DoD, and precise power distribution should be considered when developing an appropriate control scheme.

4. Conclusions

The main objective of this study was to develop an integrated review using a systematic and bibliometric approach to evaluate the performance and challenges of applying BESS technologies in MGs. According to the results observed in the review, the optimization methods for BESS present a high density and centrality, which means that the topic is under the spotlight. Researchers have applied optimization methods, to reduce installation and operation costs to a minimum. Similarly, optimization techniques were applied to determine the optimal capacity and useful life of the BESS.

BESS optimization constraints vary depending on the weather and infrastructure conditions. In addition to the degradation rate and battery life, the SoC is considered the most common operational constraint when developing an efficient BESS optimization technique; both parameters are directly related to SoC. Other factors such as cost, reliability, battery technology, power quality, frequency variations, and environmental conditions must also be considered in developing optimal BESS. However, the most common challenges in developing a BESS system are the economic factors as researchers focus on cost–benefit analysis. Battery aging must also be considered in the total cost of the system, as it directly relates to battery life. For example, when a battery is inactive, the chemicals in the BESS are active because of voltage and temperature, causing constant battery degradation known as calendrical aging. Cyclical aging is related to the charge and discharge factors of the battery. The main parameters of a BESS system must be considered to ensure the system is efficient.

CRediT authorship contribution statement

Eliseo Zarate-Perez: Investigation, Formal analysis, Software, Writing – review & editing. **Enrique Rosales-Asensio:** Investigation, Formal analysis, Software, Writing – review & editing. **Alberto González-Martínez:** Conceptualization, Investigation, Formal analysis, Writing – review & editing. **Miguel de Simón-Martín:** Methodology, Visualization, Investigation, Formal analysis, Supervision, Writing – review & editing. **Antonio Colmenar-Santos:** Conceptualization, Validation, Writing – original draft, Conceptualization, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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