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Systematic Review

A Systematic Literature Review on Li-Ion BESSs Integrated with Photovoltaic Systems for Power Supply to Auxiliary Services in High-Voltage Power Stations

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Abstract

The integration of lithium-ion (Li-ion) battery energy storage systems (LiBESSs) with photovoltaic (PV) generation offers a promising solution for powering auxiliary services (ASs) in high-voltage power stations. This study conducts a systematic literature review (SLR) to evaluate the feasibility, benefits, and challenges of this integration. The proposed SLR complies with the PRISMA 2020 statement, and it is also registered on the international PROSPERO platform (ID 1073599). The selected methodology includes the following key steps: definition of the research questions; search strategy development; selection criteria of the studies; quality assessment; data extraction and synthesis; and discussion of the results. Through a comprehensive analysis of scientific publications from 2013 to 2024, trends, advancements, and research gaps are identified. The methodology follows a structured review framework, including data collection, selection criteria, and evaluation of technical feasibility. From 803 identified studies, 107 were eligible in accordance with the assessed inclusion criteria. Then, a custom study impact factor (SIF) framework selected 5 out of 107 studies as the most representative and assertive ones on the topics of this SLR. The findings indicate that Li-ion BESSs combined with PV systems enhance reliability, reduce reliance on conventional sources, and improve grid resilience, particularly in remote or constrained environments. The group of reviewed studies discuss optimization models and multi-objective strategies for system sizing and operation, along with practical case studies validating their effectiveness. Despite these advantages, challenges related to cost, regulatory frameworks, and performance variability remain. The study concludes that further experimental validations, pilot-scale implementations, and assessment of long-term economic impacts are necessary to accelerate the adoption of BESS-PV systems in high-voltage power substations. This study was funded by the R&D program of the Brazilian National Electric Energy Agency (ANEEL) via project number PD-07351-0001/2022.

Keywords: battery energy storage system; auxiliary services; photovoltaic; systematic literature review; Li-ion batteries

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1. Introduction

Power stations (PSs) and transmission power lines (TPLs) are critical for integrating power grid components, including transformers, generators, and distribution lines. Essentially, PSs and TPLs form the regulated physical pathways for energy flow and exchange among grid elements. Disconnection events in PSs, during maintenance or tests, require planning to facilitate reconnection strategies and ensure uninterrupted energy flow via TPLs. However, unintentional disconnections, such as those caused by blackouts, may occur and require mitigation to minimize their impact during grid restoration [1,2].

The management of control, command, and supervision within a power station relies on auxiliary systems and services (ASs), which are a set of equipment and panels designed to support essential operational functions. During disconnection events, feeder circuits supplying critical loads must remain operational to enable equipment maneuvering for restoration. The IEEE Standard 1818-2017 [3] specifies that AS alternating current (AC) supply should originate from reliable sources in a hierarchical order: (i) a primary source (e.g., the tertiary winding of a power transformer or a substation bus); (ii) a secondary source (such as an external distribution line); and (iii) a diesel generator as a backup. The designation of these sources depends on criteria such as substation location, equipment specifications, and bus configurations. In contrast, direct current (DC) systems in the context of PSs are intended primarily for emergency or contingency situations [4,5], like failure of AC sources and voltage collapse. Then, the DC systems are designed to supply power to critical equipment, such as protective relays, monitoring equipment, and control circuits that operate circuit breakers or other fault isolation devices, both during interruptions and when power systems are intact.

Supplying power to auxiliary systems in the context of PSs presents challenges, particularly when power station configurations, such as switching substations, exclude the use of the tertiary winding of a transformer [6,7]. In these cases, reliance on two external feeders from the same distribution substation reduces supply reliability [8]. To address these challenges, unconventional solutions have been implemented, particularly in remote locations or areas lacking power sources. One such solution is the use of power voltage transformers (PVTs), equipment widely adopted in North America and increasingly popular due to the expansion of renewable energy across the world. These devices supply low output voltage while connecting directly to high-voltage power lines, thereby eliminating the need for auxiliary transformers [9].

The energy transition scenario, with its emphasis on renewable sources and energy storage systems, has introduced new opportunities for energy supply and storage across various applications. Lithium-ion batteries, valued for their high energy density and efficiency, are increasingly used in electrical grids to store energy, manage peak demand, and enhance infrastructure reliability [10–12]. A techno-economic feasibility analysis comparing grid-connected photovoltaic systems with stationary lithium-ion (Li-ion) battery storage found lower Levelized Cost of Energy (LCOE) and net present cost (NPC) for Li-ion batteries compared to lead–acid batteries in meeting commercial load profiles [13]. Similarly, studies on hybrid systems incorporating wind generation (WT), photovoltaic (PV), and diesel generators highlight the superior performance of Li-ion battery storage in maintaining low LCOE and NPC under varying conditions [14]. For example, a study on Gasa Island, South Korea, demonstrated that Li-ion battery energy storage within an autonomous microgrid significantly improves renewable energy penetration and reduces fossil fuel consumption [15]. Dynamic simulations of diesel generators, wind turbines, photovoltaic plants, and battery energy storage systems in hybrid microgrids also validate the role of energy storage systems in enhancing system stability, particularly by providing rapid responses during transient conditions [16].

In power transmission, microgrids incorporating photovoltaic generation and battery energy storage systems (PV-BESSs) have emerged as a viable solution for powering auxiliary systems under both normal and constrained conditions. These microgrids improve reliability and promote renewable energy use in substations. Studies have investigated maintenance-free lead–acid batteries combined with photovoltaic and wind generation as supplementary power supplies for 500 kV substations [17,18]. Off-grid microgrid simulations, optimized using tools such as HOMER Pro [19], demonstrate that configurations combining photovoltaic generation, Li-ion batteries, and diesel generators maximize solar and storage capacity while reducing reliance on diesel [20]. Further, multi-objective optimization techniques and simulations have been employed to determine the optimal sizing of PV-BESS components, ensuring robust AS power supply during contingencies [21,22]. Laboratory validations of hybrid battery energy storage systems, comprising Li-ion and lead–acid batteries, confirmed their effectiveness in maintaining microgrid voltage and frequency without load shedding [23]. A method introduced by Costa et al. [8] compensates for energy density variations among battery technologies, offering practical solutions for transmission substations in northeastern Brazil.

This study comprehensively reviews the scientific literature addressing the feasibility of integrating PV generation with Li-ion battery storage as a power source for PS auxiliary services. The hypothesis suggests that implementing these technologies in high-voltage substations can overcome challenges associated with remote locations and physical installation constraints. This study maps recent scientific advances, identifies gaps, and highlights research opportunities for further development.

By focusing on the integration of PV generation with Li-ion battery storage systems as a power source to auxiliary services in high-voltage substations, this research deals with solutions that can act as both primary and stand-alone AC power supply for auxiliary services, following the guidelines proposed by IEEE Std 1818-2017 [3]. Therefore, the authors clarify that any possible solution using a similar integration of direct current (DC) microcrids as a primary application for ASs is out of the scope of this study.

Apart from this introduction, the paper is structured as follows: Section 2 details the systematic literature review methodology, Section 3 presents the results and discussion, and Section 4 concludes with future research directions and potential actions.

2. Methodology and Research Settings

The methodology adopted in this study is primarily based on the systematic literature review (SLR) proposed by Kitchenham et al. [24,25]. This method is widely cited and relevant to the area, and the structure for this document was prepared following a report model suggested by the same authors. As a reference example of using the suggested text structure, the authors considered the one described in [26].

By using such an SLR protocol, this work aimed to critically identify, select, perform, and evaluate the maximum number of possible published scientific papers related to battery energy storage systems based on Li-ion technologies and powered by PV systems as an option for providing complementary energy sources in PSs. The authors also decided to perform this search by evaluating only scientific papers published from 2013 to 2024.

In addition, authors confirm this SLR follows the PRISMA 2020 statement paper [27] and its guidelines described in [28]. The filled PRISMA 2020 27-item checklist [29] is presented in Appendix A, and the custom PRISMA 2020 flow diagram [30] is shown in Section 3.1.2. Finally, the Abstract presented on the front-page of this study complies with the 12-item checklist PRISMA 2020 for Abstracts [31]. To enhance transparency and visibility, this study is also recorded in an international systematic review registry named PROSPERO [32] through the registration number, ID 1073599.

An online platform named Parsifal [33] was adopted by the authors to assist the management of required SLR stages and to offer a unique shared tool (effort convergence). This online platform offers a layout based on the SLR protocol proposed by [24,25], which also justified its adoption in this work. Basically, the authors considered the following procedure steps available on the Parsifal platform: review, planning, conducting, and reporting. As shown in Figure 1, the conduction section is composed by the following critical SLR steps: search, import studies, study selection, quality assessment, data extraction, and data analysis.

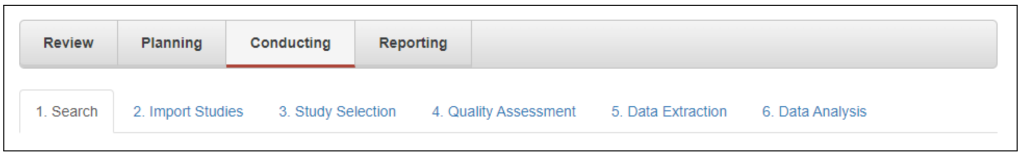

Figure 1. Layout from the online Parsifal platform [33], which was adopted in this work.

According to Kitchenham and Charters [24] and Kitchenham and Brereton [25], the stages associated with planning a review are identification of the need for a review; commissioning a review (optional); specifying the research questions; development of a review protocol; and evaluating the review protocol (optional). The same documents also suggest the stages associated with conducting the review as follows: identification of research; selection and validation of studies; study quality assessment; selection of primary studies; data extraction and monitoring; and data synthesis. The following subsections describe those stages and how they were involved by the authors in the proposed SLR. They are described on a comprehensive order, which possible overlaps and redundancies were minimized.

2.1. Review Questions

This work performed an SLR based on one primary goal: reviewing the state of the art of energy storage systems based on Li-ion batteries combined with PV power generation systems and for the power supply source for auxiliary systems in power stations.

Then, a group of specific review (or research) questions was considered for selecting potential primary studies and supporting data extraction/analysis. The review questions adopted here are presented in Table 1. These review questions were applied only to a group of considered (or eligible) sources, excluding the duplicated ones. Both inclusion (considered) and exclusion (discarded sources) criteria are further described in Section 2.2.

Table 1. Research questions settled by the authors while conducting the proposed SLR.

ID	Question
RQ1	What are the most significant scientific papers published between 2013 and 2024 [1] (last decade) that explore the use of Li-ion battery energy storage systems (LiBESSs) in conjunction with PV generation as a power supply source for power stations?
RQ2	Considering other energy sources beyond photovoltaic (PV) generation, what are the key battery technologies and their applications in the context of PSs?
RQ3	What are the main themes or applications addressed, and what trends suggest the most promising areas for future research?

[1] Only whole years were considered.

2.2. Review Methodology

2.2.1. Data Sources and Search Strategy

The review protocol considered for this work was based on a method known as population, intervention, comparison, outcome, and context (PICOC), which had been originally proposed by [34]. The same review protocol was adopted in review structures described in [24,26]. The PICOC method, or criteria, is based on the following terms: population (which defines searching limits in an application area or an industry groups); intervention (it addresses a specific issue observed in the population); comparison (of standards and other reference procedures with a specific intervention previously addressed); outcomes (what should be performed along the review and how); and context (where the intervention comparison takes place and whether it depends on the application defined by the population).

During the SLR proposed here, scientific papers (and similar technical publications) were collected from the following data resources (in alphabetical order): IEEE Digital Library [35]; ScienceDirect [36]; Scopus [37]; and Web of Science [38]. These four database resources were selected based primarily on their comprehensiveness and relevance in the field of electrical engineering, which corresponds to a similar background area among the authors and topic of this research. Due to the fact that selected data resources correspond to online platforms available on the internet, the search method was performed only digitally. According to the available studies from each data resource, a list of correspondences between keywords and synonyms (Table 2) was also considered for covering a wider range of similar research.

Table 2. List of considered keywords and synonyms.

Keyword	Synonyms
Auxiliary services	Auxiliary systems
Battery energy storage	BESS or battery energy storage system
Lithium ion	Li-ion
Photovoltaic	PV or solar photovoltaic
Power supply	Power backup
Substations	Switching substations

Based on Table 2, it was possible to specify search strategies using logical (Boolean) operators like "AND" and "OR". Initial tests were performed to identify closenesses among searching strategies, resulting in a more effective search methodology. For instance, the authors noticed that combining the keyword "Battery Energy Storage" with other terms from Table 2 results in a higher number of covered papers compared to the same term combinations by using the keyword "Battery Energy Storage Systems". Apparently, due either to a higher paper visibility or to a restricted number of characters (in the title, mainly), other authors decided to refer to these kinds of systems by omitting the term "Systems". Such a simple example shows that a common approach would yield a limited selection, restricting the option with a higher number of found papers. However, such an approach might restrict the search covering range by excluding those papers whose authors decided to include the term "Systems" in their respective published titles. Therefore, taking into account the main purpose of this work (an SLR), a better option seems to be merging both options at first and then filtering the entire collection by removing duplicates and out of context studies.

Following such observations while polishing search strategies and dealing with feature limitations from the chosen data sources, a group of nine adjusted search strings were finally specified for this work. Table 3 describes each of those search strings, as well their respective covered topics and Boolean engines. Due to a feature limitation on the platform ScienceDirect (only), some search strings described in Table 3 required a Boolean engine minimization. Minor adjustments on such strings were carefully made to fit them into the platform requirements [36] without diminishing the search strategy proposed here.

Table 3. List of search strings applied to the group of selected (scientific) data resources.

ID	Covered Topics	Search String (Boolean Engine)
S1	BESS, Li-ion, PV, and power systems	(*BESS* OR *Battery Energy Storage Systems* OR *Battery Energy Storage*) AND (*Li-ion* OR *Lithium-ion* OR *Lithium Ion*) AND (*Solar* OR *Photovoltaic* OR *PV*) AND (*Transmission* OR *Distribution*)
S2	BESS, Li-ion, PV, and power stations	(*BESS* OR *Battery Energy Storage Systems* OR *Battery Energy Storage*) AND (*Li-ion* OR *Lithium-ion* OR *Lithium Ion*) AND (*Solar* OR *Photovoltaic* OR *PV*) AND (*Substations* OR *Switching Substations*)
S3	BESS, Li-ion, PV, and auxiliary systems	(*BESS* OR *Battery Energy Storage Systems* OR *Battery Energy Storage*) AND (*Li-ion* OR *Lithium-ion* OR *Lithium Ion*) AND (*Solar* OR *Photovoltaic* OR *PV*) AND (*Auxiliary Services* OR *Auxiliary Systems* OR *Auxiliaries*)
S4	BESS, Li-ion, PV, and black start	(*BESS* OR *Battery Energy Storage Systems* OR *Battery Energy Storage*) AND (*Li-ion* OR *Lithium-ion* OR *Lithium Ion*) AND (*Solar* OR *Photovoltaic* OR *PV*) AND (*Black Start* OR *Black-start* OR *Blackstart*)
S5	BESS, Li-ion, PV, and isolated systems	(*BESS* OR *Battery Energy Storage Systems* OR *Battery Energy Storage*) AND (*Li-ion* OR *Lithium-ion* OR *Lithium Ion*) AND (*Solar* OR *Photovoltaic* OR *PV*) AND (*Off grid* OR *Islanded*)
S6	Power stations, BESS, PV, and auxiliary systems	(*Substations* OR *Switching Substations*) AND (*BESS* OR *Battery Energy Storage Systems* OR *Battery Energy Storage*) AND (*Solar* OR *Photovoltaic* OR *PV*) AND (*Auxiliary Services* OR *Auxiliary Systems* OR *Auxiliaries*)
S7	Power stations, BESS, PV, and black start	(*Substations* OR *Switching Substations*) AND (*BESS* OR *Battery Energy Storage Systems* OR *Battery Energy Storage*) AND (*Solar* OR *Photovoltaic* OR *PV*) AND (*Black start* OR *Black-start* OR *blackstart*)
S8	Power stations, BESS, PV, and isolated systems	(*Power Stations* OR *Switching Substations*) AND (*BESS* OR *Battery Energy Storage Systems* OR *Battery Energy Storage*) AND (*Solar* OR *Photovoltaic* OR *PV*) AND (*Off grid* OR *Islanded*)
S9	Power stations, BESS, PV, and power backup	(*Substations* OR *Switching Substations*) AND (*BESS* OR *Battery Energy Storage Systems* OR *Battery Energy Storage*) AND (*Solar* OR *Photovoltaic* OR *PV*) AND (*Power Supply* OR *Emergency Supply* OR *Backup*)

The first five search strings (S1–S5) combine the terms BESS, Li-ion, and PV with a fourth term (power systems, power stations, auxiliary sytems, black start, or isolated systems). The last four search strings (S6–S9) do the same by using the terms power stations, BESS, PV and a new fourth term: auxiliary systems; black start; isolated systems; or power backup. The number of studies collected by all these nine search strings and the way they were classified in this work are described as follows.

2.2.2. Study Selection

Based on the search strings described in the Table 3, this work deliberated over a total of 36 different search engines (nine search strings for each of four data resources) in February 2025. As a result, they provided an entire collection of 803 publication reviews from all data resources. Each adjusted search string contributed the following number of collected studies: (S1) +317; (S2) +24; (S3) +33; (S4) +3; (S5) +287; (S6) +15; (S7) +3; (S8) +39; and (S9) +82 studies.

Figure 2 presents a distribution of individual contributions from each data resource per search string within the entire found collection. It highlights the relative impacts of the S1-S5-S9 strings and IEEE/Scopus databases on the SLR proposed by this work.

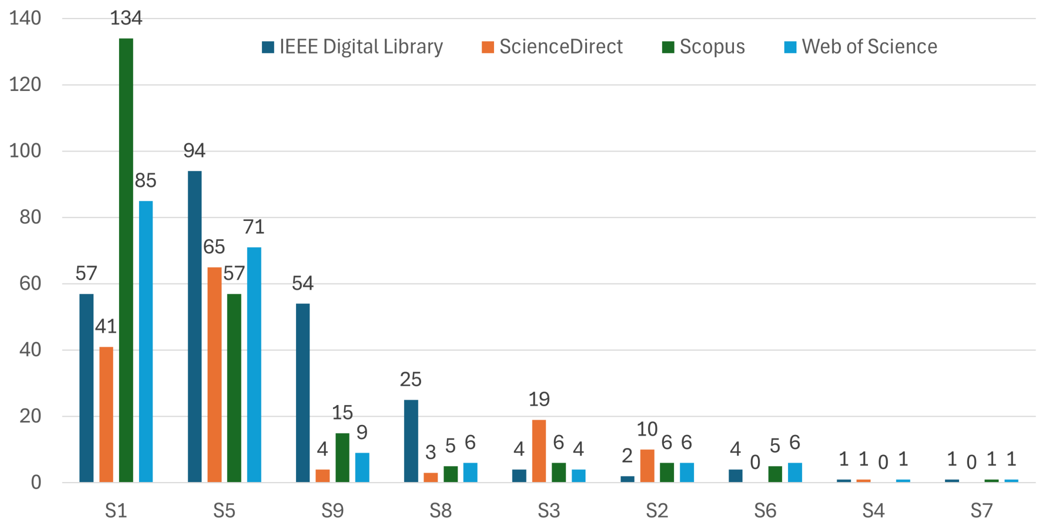

Figure 2. Distribution of found studies (entire collection) among data resources and search strings.

By contrast, the S4-S7 strings did not offer notable contributions, and, apparently, this suggests both adjusted Boolean engines might be too restrictive. Another reason for that relies on a possible lack of studies intended to cover three topics at once: black start, BESSs, and PVs.

As expected, the entire obtained collection of 803 publication reviews is composed of individual and duplicated studies. The group of review publications must be composed only by single studies (here labeled as considered studies). Details about removing multiple studies and other results related to study selection are discussed in Section 3.1.1.

2.2.3. Included and Excluded Studies

According to Kitchenham and Charters [24] and Kitchenham and Brereton [25], once the potentially relevant considered studies have been obtained, they should be assessed for their actual and direct impacts on the proposed SLR. At first, a list of inclusion and exclusion criteria must be defined in consonance with review questions. Then, inclusion and exclusion criteria guide the selection of a new group of validated studies which are now classified as "accepted".

Based on Table 1 and characteristics observed in Figure 2, this work settled a list of inclusion and exclusion criteria which are described in Table 4. Such a list was specified to catch studies mainly related to Li-ion battery energy storage systems (LiBESSs) integrated with PV systems (LiBESS-PV) in terms of the following applications: overall operation and performance control; power of ancillary systems; or power unit source.

In this work, an expected higher number of exclusion criteria matches with a more detailed (or sensitive) study categorization. After processing one more round of study selection, the items listed in Table 4 also justify why one specific study should be now relabeled as "accepted" or not (rejected). For instance, any previously selected study integrating LiBESSs with any renewable source rather than PV generation should (at this new round of study selection) be classified as out of scope (or irrelevant) and rejected for this work.

In summary, such new labeling means that all the previous considered (single) studies are now divided in two subgroups: the accepted and rejected studies. Evidently, only the subgroup of accepted studies is valid to be carried out to the next stage of the SLR. Details about both subgroups and more results are presented and discussed in Section 3.1.2.

Table 4. List of considered inclusion and exclusion criteria.

No.	Why Include?	Why Exclude?
1	LiBESS-PV as an off-grid power source	LiBESS integrated with a renewable source which is not PV
2	LiBESS-PV applied to ancillary services	LiBESS-PV applied to DC microgrids
3	Operation control of combined LiBESS-PV systems	Out of the scope of this work
4	–	Publication year earlier than 2013
5	–	Related to either distributed generation (DG) or distribution power systems
6	–	Related to either electrical vehicles or vehicle charging stations
7	–	Related to traction (power) substations

2.2.4. Study Quality Assessment

In addition to the inclusion and exclusion criteria, a critical part of the SLR must be performed on the subgroup of (here called) accepted studies: a quality assessment. As there are many possible interpretations on judging how qualified a study is, the adoption of a previously tested protocol is a reasonable option. As suggested in [24–26], an assertive study quality assessment comes from a balance between bias minimization and maximization of both internal and external validities.

The term bias refers to a systematic error and it evidences a forced (intended or not) tendency on the results. It might affect the overall conclusions of an SLR since biased results minimize the level of heterogeneity in the answers for the initially proposed review questions. As this work selected an initially wide number of studies (entire collection) and properly dealt with the SLR stages, it can be assumed a minimization of bias impacts was achieved.

The term internal validity refers to the procedures adopted while designing and conducting the SRL. Another part of the internal validation relies on the achievement of unbiased results. As this work initially discarded duplicated studies (as discussed in Section 2.2.2) and then performed a careful analysis in the last round of study selection (as discussed in Section 2.2.3)—including an overlapped analysis of each paper from different people while categorizing it in accordance with Table 4—it can be concluded that an internal validity maximization was achieved.

Finally, the external validity refers to the generalization of characteristics observed in the group of accepted studies that are representative and significant in the topics covered by the SLR. Obviously, a impartial method should be applied to identify such possible contributions. Following the assumption that all the (subgroups of) accepted studies selected for this work are unbiased and internally valid, their individual impacts (i.e., their individual external validity) can be measured by means of a numerical quality score.

In this work, a quality score value is refereed to as the "study impact factor" (SIF). Originally proposed in [39], the SIF aims to quantify a potential applicability of a study in the context of topics covered by the proposed SLR. Based on [25], this work measured the SIF of each accepted study as described in (1).

$$\mathrm{SIF} = \sum_{i=1}^{m} \mathrm{AQ}_i \quad (1)$$

Limited to one value per study, the term AQ_i corresponds to a score defined by an answer which best fits to the assessment question (AQ) number i. In total, each accepted study has m individual answers (or scores) to an entire set of m assessment questions.

So as to measure individuals SIF values from the group of accepted papers, this work proposes five different assessment questions ($m = 5$) with three possible answers each. Table 5 describes these assessment questions and their score points for each possible answer.

Table 5. SIF estimation: list of assessment questions and possible answers (with scores).

ID	Assessment Question (AQ)	Yes	Somehow	No
AQ_1	Is it possible to classify the study as a primary study? (neither a review study nor a gray paper)	1.0	0.5	0.0
AQ_2	Does the study either discuss or describe the use of an LiBESS integrated with PV generation?	1.0	0.5	0.0
AQ_3	Is it possible to link the study with a power or energy provision in the context of auxiliary systems in power substations (or power stations)?	1.0	0.5	0.0
AQ_4	Is it possible to extract any procedure or method from the study which can be applied to either power sources supplying power substations (power source) or the provision of ancillary services (grid quality)?	1.0	0.5	0.0
AQ_5	Does the study either discuss or propose the use of LiBESS-PV in the context of AC microgrids?	1.0	0.5	0.0

As suggested by Kitchenham et al. [24,25], the assignment of answers "Yes", "Somehow", and "No" (as presented in Table 5) while evaluating the quality assessment questions does not correspond strictly to an objective judgment in terms of an absolute sense. Rather, it consists of a systematic and rigorous process designed to minimize subjectivity through standardization and agreement among multiple reviewers. Briefly, the "Somehow" option aims to capture situations where a criterion is not fully met ("Yes") but also not entirely absent ("No"), thus reflecting the complexity of methodological rigor in this study.

Additionally, to minimize possible bias and subjectivity while assessing the quality of the selected studies, the authors established the following approach: every single selected study should be evaluated by three or more authors of this study. Our approach was also based on what is suggested by Kitchenham et al. [24,25]: "Whenever feasible, data extraction should be performed independently by two or more researchers. Data from the researchers must be compared and disagreements resolved either by consensus among researchers or arbitration by an additional independent researcher".

From Table 5, it can be noticed that accepted studies were then sorted in terms of significance (a primary or secondary study selection, as in AQ_1) and closeness to the main topic of interest from the here proposed SLR: LiBESS-PV generation systems for power supply of ASs in power stations. Such closeness was separately quantified in individual research topics by means of scores for assessment questions AQ_2–AQ_5.

The individual SIF values achieved by all the accepted studies, as well more results concerned with quality assessment, are presented and discussed in Section 3.1.3.

2.2.5. Data Extraction

In the context of an SLR, the data extraction process allows the authors to draw more accurate conclusions and to establish correlative information based on the collective (data) perception [40]. Basically, as presented in [41], data extraction can be defined as the process of capturing key characteristics of (selected) studies in a structured form.

According to Kitchenham and Charters [24] and Kitchenham and Brereton [25], a data extraction should be performed independently by two or more researchers, followed by a group discussion to achieve a consensus among all researchers and to avoid inconsistency with extracted data. Therefore, all the authors of this work got involved with activities concerned with data extraction design, application, and group discussion (online, mainly). Before that, key issues such as analyzing multiple studies and a full understanding of data extraction process were also intensively discussed in group.

In this work, the authors propose the use of a data extraction form described in Table 6. Mainly approached for meeting the procedures of this SLR, the data extraction form was designed for supporting data analysis and providing enough information to answer the review questions. Therefore, each of the seven extraction form fields EF1–EF7 presented in Table 6 is (partially or fully) related to one of the review questions from Table 1.

Table 6. Description of data extraction form proposed and used in this work.

Field	Specific Question	Ref. to (Table 1)	Answer Type	Expected Values
EF1	What is the main objective of the study?	RQ1	Unlimited	Single paragraph text.
EF2	How do the authors propose to achieve that main objective?	RQ1	Unlimited	Single paragraph text.
EF3	Does the study propose using any other energy source besides PV? If so, which ones?	RQ2	Multiple choice	Biomass, diesel generator, geothermal, heat concentration, hydropower, wind energy, other, or not applicable.
EF4	Which techniques (or applications) are involved in the objective of the study?	RQ2	Multiple choice	Ancillary (or grid) services, black start, power source, other, or not applicable.
EF5	Which battery storage technologies are covered in the study?	RQ2	Multiple choice	Flow batteries, lead–acid batteries, Li-ion (lithium iron phosphate), Li-ion (other technologies), supercapacitors, or other.
EF6	(Optional) What are the identified challenges/issues and respective impacts on the main objective of the study?	RQ3	Unlimited	Single paragraph text or not applicable.
EF7	What are the conclusions and results from the study?	RQ3	Unlimited	Single paragraph text.

As noticed in Figure 1, the online Parsifal platform [33] allows users to write and use their own data extraction forms. Based on the form presented in Table 6, the authors evaluated each publication from the group of accepted studies (i.e., the same group analyzed in the study quality assessment) and registered the respective answers on the Parsifal platform. The results and main perceptions from data synthesis are discussed in the following section.

3. Results and Discussion

The here proposed SLR required several consecutive activities in the different stages the study selection, analysis, synthesis, and discussion. Following the description of methodology and research settings previously discussed, this section presents the results and data interpretation obtained while performing both quantitative and qualitative analysis.

So as to exemplify the several stages of study selection, the authors decided to revisit parts of the methodology and detail their inner aspects based on the achieved results. Although revisiting parts of this manuscript might emerge as a redundant action, the authors believe its reading and better comprehension justify such an approach. Therefore, a quantitative analysis is presented and discussed.

After that, some lines of argument synthesis, correlations, and data interpretation were combined and discussed by the authors in terms of a qualitative analysis. As a consequence, quantitative and qualitative results are here synthesized separately, as well as their suggested inferences. Lastly, this section also links the overall findings with the review questions proposed for this SLR. And highlights on answering each review question are discussed.

3.1. Quantitative Analysis

3.1.1. Study Selection

In accordance with Section 2.2.2, a deliberate large number of 803 selected (and original) studies was successfully achieved due to the set of nine search strings described in Table 3. Such an achievement corresponds to the first round of study selection of this SLR. The second round dealt with a deeper check-up on the entire collection to identify duplicated contributions, which might be gathered from different data resources or not (i.e., a platform's inner malfunction).

As it is shown in Figure 3, 279 duplicated studies were identified and discarded. Then, the first two rounds of study selection validated (or restricted) a group of 524 publication reviews to be carried on by the SLR performed in this work. Table 7 classifies these selected studies according to their own data sources. Percentages suggest a remaining relative influence of the IEEE/Scopus databases (approx. 60%) on the group of 524 considered studies.

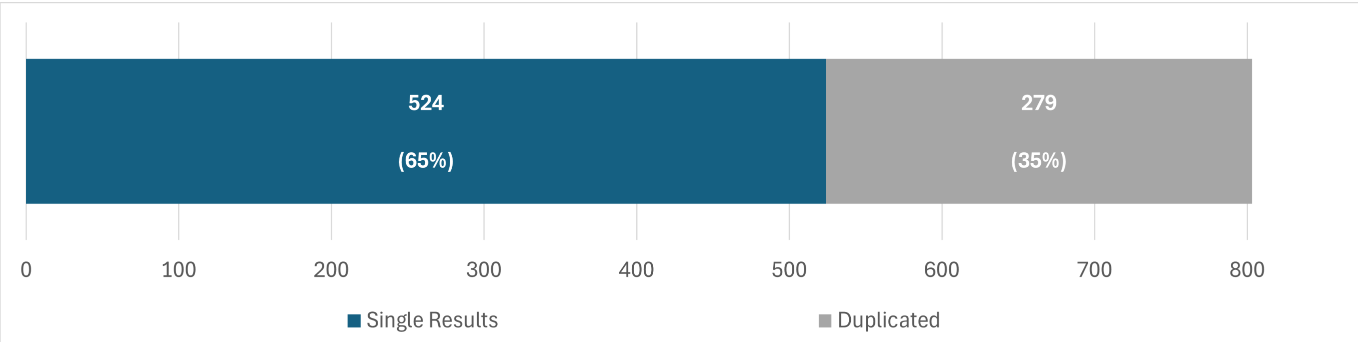

Figure 3. Proportions of considered and discarded studies within the entire collection.

Table 7. Distribution of considered publications among data sources (in addition to Figure 3).

Source	Number of Studies	%
IEEE Digital Library [35]	188	35.9%
Scopus [37]	128	24.4%
Web of Science [38]	122	23.3%
ScienceDirect [36]	86	16.4%
Total, considered studies only	524	100.0%
Entire collection (with duplications)	803	—

3.1.2. Included and Excluded Studies

Based on Table 4, a careful categorization of the group of 524 previously considered studies was conducted. As a result, 107 studies (approx. 20%) were relabeled as "accepted" and forwarded to the next methodological stage. In addition, Figure 4 presents a final distribution of chosen inclusion and exclusion criteria (Table 4) while defining the acceptance of studies or not. Distribution curves suggest two prior remarks: a significant number of studies devoted to the primary goal for this work with operational control of integrated LiBESS-PV systems and a shallow correspondence between the here proposed research questions and the studies mainly related to either distributed generation (DG) or distribution power systems.

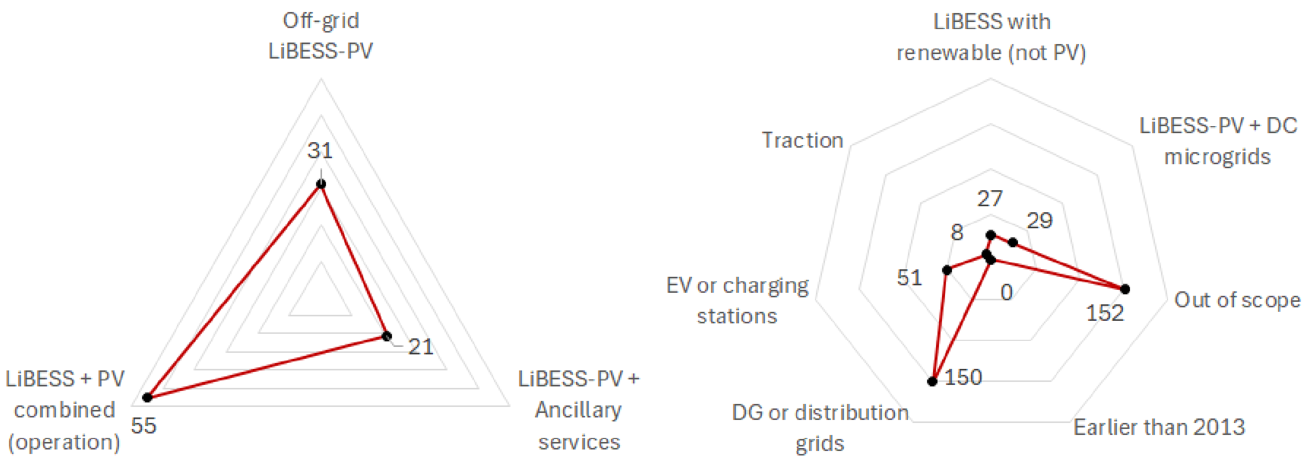

Figure 4. Distribution of inclusion/exclusion criteria (Table 4) among the accepted/rejected studies.

As proposed in this work, study selection was restricted to papers published between 2013 and 2024. In this sense, Figure 5 presents a year-based distribution of the entire group of 107 accepted studies. Although limited to a group of publications, apparently curves in Figure 5 suggest a similar publication rate (per year) until 2019, with a significant expansion of studies per year beginning in 2020. These remarks partially validate the here adopted search methodology, and they justify one key motivation for this work: an SLR on LiBESS-PV systems for the power supply of ASs in power stations.

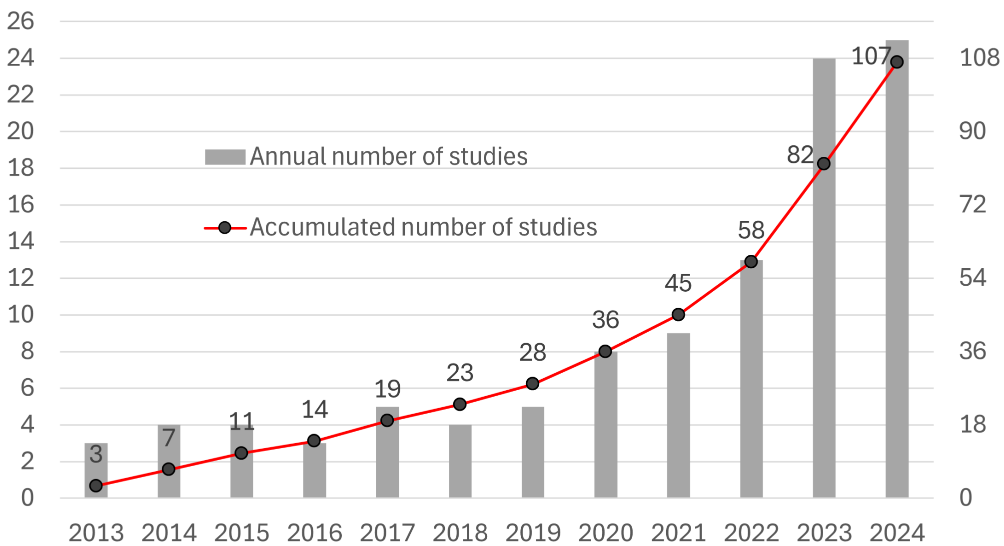

Figure 5. Annual and cumulative distribution for the 107 accepted studies.

In accordance with the PRISMA 2020 statement paper [27,28], Figure 6 shows the PRISMA 2020 flow diagram designed for this SLR [42]. This type of design is associated with systematic reviews which include searches of databases and registers only, which is the case for this study. The presented flow diagram was generated using a tool named Shiny App, available in [43], which allows researchers to develop a personalized flow diagram that conforms to the PRISMA 2020 guidelines.

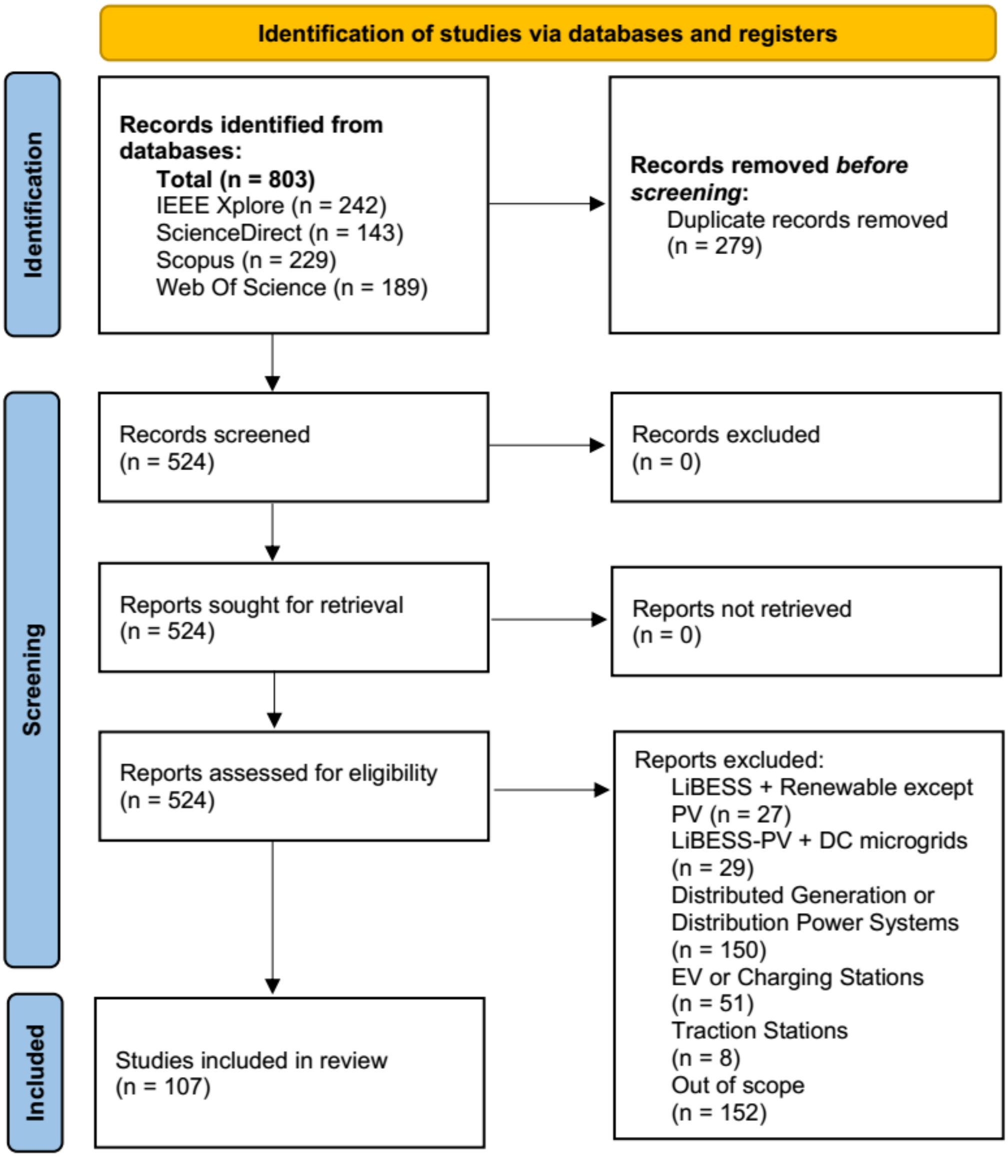

Figure 6. The PRISMA 2020 flow diagram designed for this SLR [27,42,43].

3.1.3. Study Quality Assessment

Figure 7 presents a quantitative distribution of answers registered by the group of 107 accepted papers for each assessment question described in Table 5. A similar number of answers registered as "Somehow" (score = 0.5) on all the assessment questions can be noticed. As expected for an SLR, it suggests a majority of neutral (or medium applicability/relevance) studies among the 107 accepted papers.

On the other hand, AQ_1, AQ_2, and AQ_5 registered the top-three highest quantities of positive answers, "Yes" (score = 1.0), suggesting that they might offer a higher influence on sorting the accepted studies. AQ_3 registered more negative answers, "No" (score = 0.0), than positive, which might indicate a low number of existing studies related to either auxiliary services or power stations on the topics proposed by this SLR. And AQ_4 received the highest number of "Somehow" (score = 0.5) answers, suggesting methods were partially described among the 107 studies. At least these are possible conclusions based on the time (observation) window settled for this work (2013–2024).

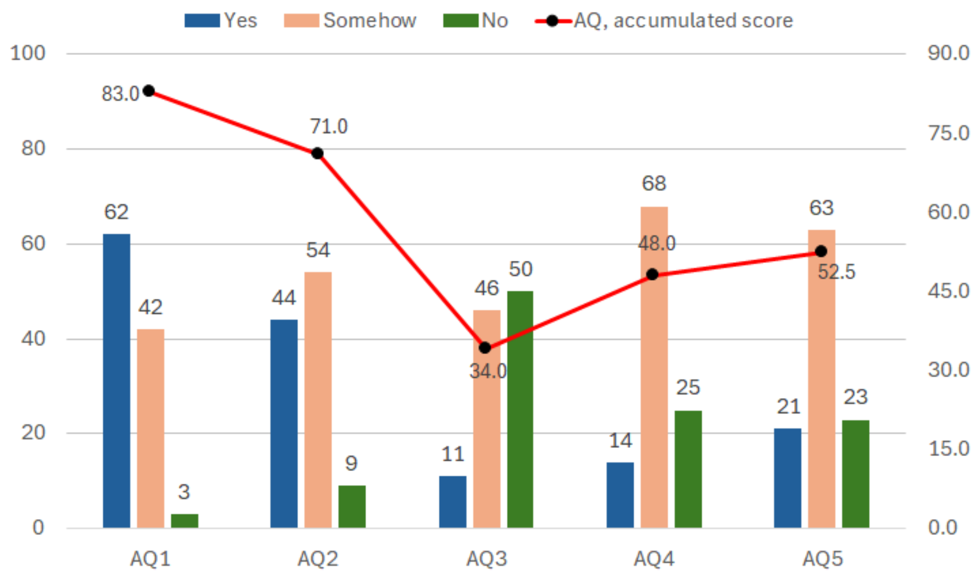

Figure 7. Registered answers per AQ (Table 5) from the group of accepted papers.

A secondary curve shown in Figure 7 also reflects such observations due to an estimation of accumulated scores per AQ. Following the respective weights presented in Table 5, the number of registered answers per AQ provides an average value of how pertinent an AQ might be. Again, AQ_1, AQ_2, and AQ_5 appear to be the most predominant ones (on average).

Based on the individual registered answers per AQ (as shown in Figure 7), each of the 107 accepted papers got sorted out according to (1). As a result, an individual SIF value per study was estimated and a summary of all those achievements is presented in Table 8.

Table 8. Summary of individual SIF values achieved by all the 107 accepted studies.

SIF	Quantity (Studies)	%	Ref. (Studies)	Relevance [2]
5.0	4	3.7%	[8,20,22,23]	High
4.5	1	0.9%	[6]	High
4.0	–	–	–	High
3.5	14	13.1%	[15,17,44–55]	Medium
3.0	19	17.8%	[14,16,56–72]	Medium
2.5	52	48.6%	[13,18,73–122]	Medium
2.0	10	9.4%	[123–132]	Medium
1.5	2	1.9%	[133,134]	Low
1.0	4	3.7%	[135–138]	Low
0.5	1	0.9%	[139]	Low
0.0	–	–	–	Low

[2] In terms of the here proposed SLR.

Following the discussion derived from Figure 7, Table 8 also indicates a major number of studies with SIF values accommodating the range from 2.0 to 3.5. Studies in this performance middle range might be related to the application of LiBESS-PV generation systems for power supply of auxiliary systems in power stations, but generally they offer contributions to isolated topics like storage devices, control methods, and projected operation scenarios (grid analysis, microgrids, etc.). Then, in terms of the here proposed SLR and its main topic of interest, the authors labeled all the studies in the middle range with a "medium" relevance. Their contributions are dispersed, suggesting they might not be fully eligible to provide assertive answers for the here proposed reviewing questions.

However, assertive information might be extracted from studies with an estimated SIF value in the range from 4.0 to 5.0. The authors adjusted a cutoff SIF level of 4.0 due to its higher potential of grouping studies that provide consecutive positive answers "Yes" to almost all the here proposed assessment questions. For this upper range, the authors labeled a group of five studies as the "highly relevant" ones. It means that, from 2013 to 2024, the respective contributions and discussions proposed in the studies listed in Table 9 can be classified as highly close to the main topic of interest covered by this proposed SLR. In complement to Table 8, Table 9 details these highly relevant studies in terms of publication year, type of contribution (conference or journal paper), author reference, and title.

Table 9. Detailed main data from the five studies classified as highly relevant in this SLR.

SIF	Ref.	Year	Type [3]	Authors	Title
5.0	[20]	2021	C	Letebele, M and Van Coller, J.	Grid-independent (renewable) hybrid power sources for the supply of transmission switching substation auxiliaries.
5.0	[8]	2023	J	Costa et al.	Development of a method for sizing a hybrid battery energy storage system for application in AC microgrid.
5.0	[22]	2023	J	Goncalves et al.	Optimal sizing of a photovoltaic/battery energy storage system to supply electric substation auxiliary systems under contingency.
5.0	[23]	2023	J	de Araujo Silva Junior et al.	Characterization of the operation of a BESS with a photovoltaic system as a regular source for the auxiliary systems of a high-voltage substation in Brazil.
4.5	[6]	2023	J	de Morais Cavalcanti et al.	Case studies for supplying the alternating current auxiliary systems of substations with a voltage equal to or higher than 230 kV.

[3] Study published as a (C) conference or (J) journal paper.

Although the authors recognize that a group of accepted studies significantly contributed to their specific publication fields, some of them achieved an SIF value lower than 2.0. In this case, they were here labeled as "low-relevance" studies as they might have provided negative answers, "No", to basically all assessment questions. Therefore, low-relevance studies were disregarded (in this SLR) while attempting to answer the here proposed review questions.

In summary, an overview of all stages involved in the study selection in this SLR is shown in Figure 8. From an initial group of 803 studies collected by the search strings described in Table 3, a final group of only five highly relevant studies was elected by (1). Alternatively, Figure 8 also exemplifies the methodology and procedures followed in this SLR while pursuing the most assertive information possible for the aimed state-of-the-art review.

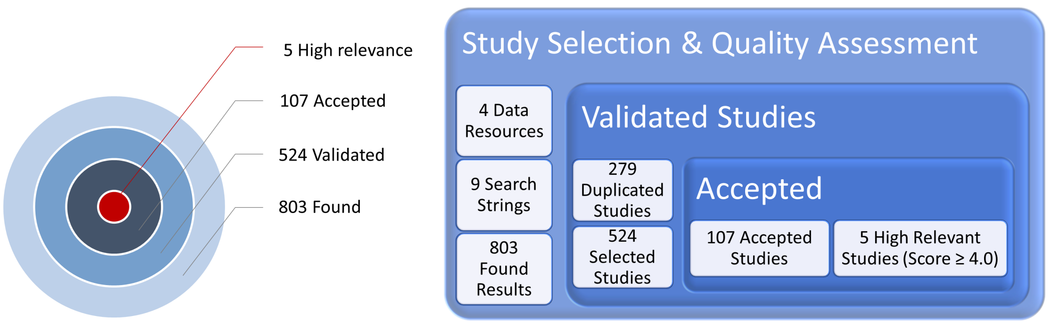

Figure 8. SLR stages and transitions in rounds of study selection and quality assessment.

3.2. Qualitative Analysis

3.2.1. Noticed Correlations

The study selection process categorized publications into multiple groups. As described in Sections 2.2 and 3.1, this work labeled groups of studies by means of the following terms (from top to bottom in terms of quantity): collected, considered, discarded, rejected, accepted, and highly relevant studies. Although a qualitative analysis is mainly defined in terms of the accepted and highly relevant studies, there are other correlations and possible inferences available from a wider group of studies.

Based on such analysis, some correlations were identified in the initial group of 803 selected studies and remained valid also in the group of 524 considered studies. One noticed correlation is presented in Figure 9. The shown treemap graph highlights the top-10 most mentioned keywords among the group of 107 accepted studies. Renewable energy, energy storage, and microgrid were identified, suggesting that the here proposed SLR might contribute to either parallel or isolated research on this list of applications.

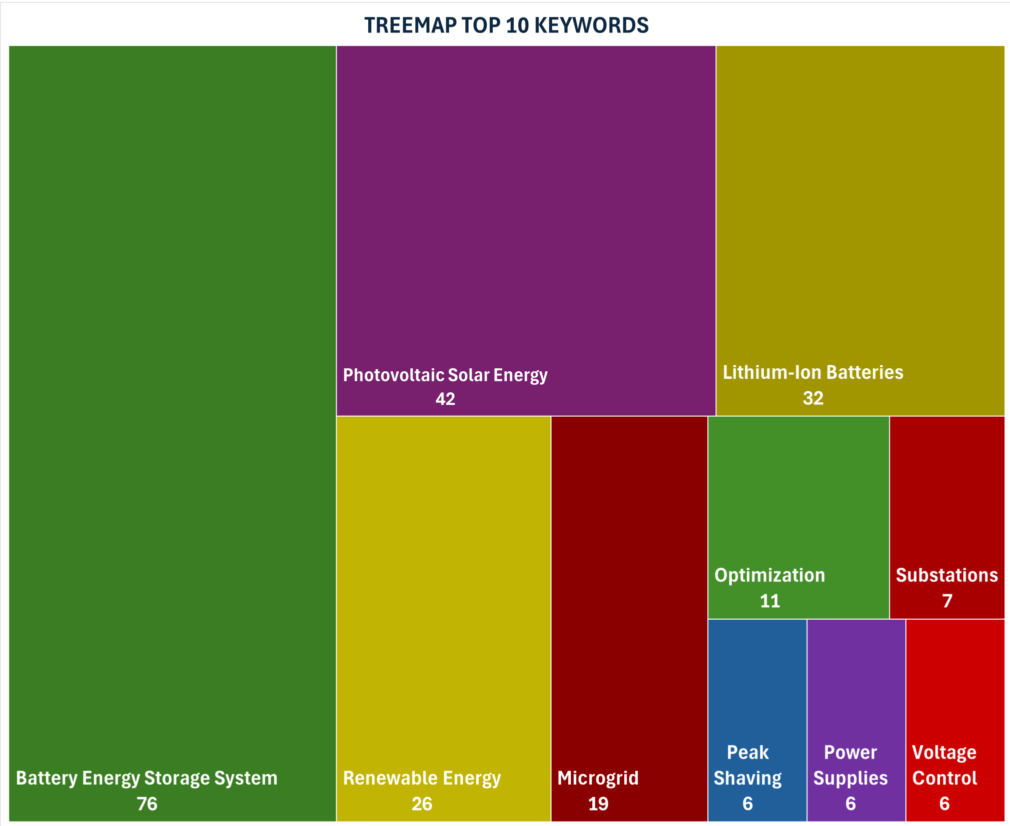

Figure 9. A treemap graph scaling the top-10 most mentioned keywords available in the group of selected publications.

During the analysis of keyword co-occurrence (as shown in Figure 9), a considerable terminological dispersion was observed in the selected studies, resulting from the use of synonyms and semantic variations to express similar concepts. Terms such as microgrid and microgrids, renewable energy and renewable energy sources, as well as variations like lithium-ion batteries and lithium-ion battery, were used interchangeably by the authors. Similarly, expressions related to storage, such as battery energy storage system, battery energy storage, battery storage, and battery, and those associated with photovoltaic generation, such as photovoltaic and solar energy, also showed significant redundancy in the datasets. So as to ensure visual clarity and analytical consistency in the co-occurrence maps and treemap generated, a synthesis of similar keywords was carried out, consolidating semantically equivalent terms under a single representation. Terminological harmonization, in addition to improving the presentation of results, ensured greater robustness in identifying key themes and emerging trends related to the integration of photovoltaic systems and battery energy storage.

A smaller number of keywords like battery energy storage systems, batteries, substation, and li-ion technologies were also identified among the accepted studies. The existence of this minor group of isolated studies might justify the here proposed SLR, which promotes an association among different devices in the context of energy storage technologies applied to power substations and renewable sources.

Additionally, Figure 10 presents a visual network of concurrence applications extracted from the group of 107 accepted studies. This graph was elaborated using the VOSviewer platform (version 1.6.20) [140], which applies a set of different colors to highlight a specific cluster of keywords within the co-occurrence network. Then, keywords within the same cluster (i.e., of the same color) tend to co-occur more frequently with each other rather than with keywords from other clusters.

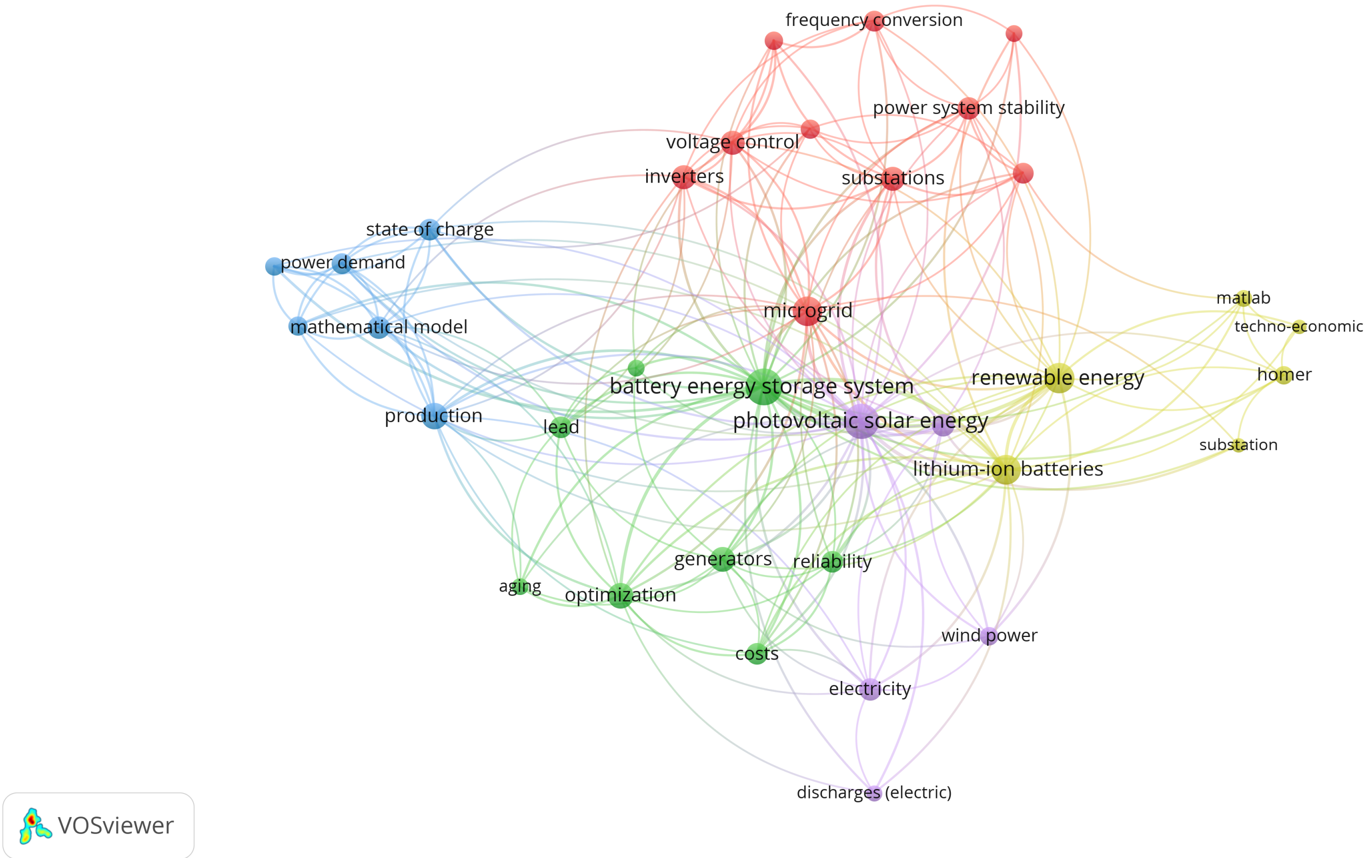

Figure 10. A network visualization graph presenting concurrences among the keywords shown in Figure 9. This graph was elaborated using the VOSviewer platform (version 1.6.20) [140].

Therefore, the network presented in Figure 10 evidences the noticed application interconnections and how intensely (in terms of quantity) these applications got covered by studies published over the last decade, 2013–2024. Once again, a possible "pin location" for this proposed SLR could be addressed between the green and purple dots located in the center of graph shown in Figure 10. Then, this pin on such network graph also exemplifies how close other applications are from the main topic of interest in this proposed SLR: LiBESS-PV generation systems for the power supply of auxiliary systems in power stations.

Figure 11 presents a heat map based on the time lapse for the network visualization graph shown in Figure 10. A more recent pattern from the green and yellow curves, which are directly associated with the here proposed SLR, can be noticed.

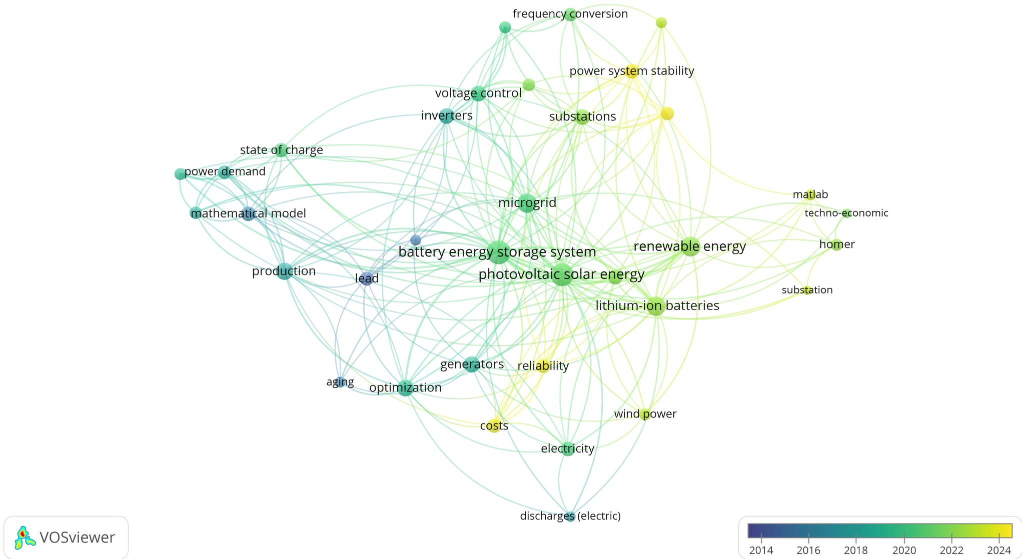

Figure 11. A heat map feature presenting a time line perspective of the network visualization graph shown in Figure 10. This graph was elaborated using the VOSviewer platform (version 1.6.20) [140].

In this study, the authors decided to apply a set of colors in Figure 9 that reflect the way the data results are presented in Figures 10 and 11. Basically, a similar set of applied colors within the graphs makes easier a possible comparison among them and enhances a better understanding of the data results. As a result, one similar aspect is shown by comparison of the treemap in Figure 9 with the heat map shown in Figure 11: both graphs evidence a higher rate of recent studies which combine the topics of battery energy storage systems, PV systems, and (power) substations.

Although advances in using supercapacitors and new current control strategies are out of context in terms of the here proposed SLR, Figure 11 suggests both of those topics have been in evidence recently and might indicate a research trend for the next 5–10 years. Going further from the time lapse considered in Figure 11, the authors estimate the development and availability of other energy storage technologies in the next 10 years (2025–2035) might also contribute to a higher scalability of using them in the context of power substations and the supplying of auxiliary services.

3.2.2. Data Synthesis

According to the methodological guidelines proposed by Kitchenham et al. [24,25], a data synthesis stage in an SLR should be conducted in a structured, transparent manner and based on evidence extracted from the selected primary studies. This stage can adopt descriptive, qualitative, or quantitative approaches depending on the type of extracted data and settled research questions.

In this work, a descriptive and categorized data synthesis was chosen with the goal of organizing extracted data around five main analysis axes: study objective, applied methodology, storage technologies, energy sources complementary to the photovoltaic system, and functional application of PV-BESSs. The categorization was performed based on recurring attributes in the 107 accepted studies, enabling the identification of trends, patterns, and gaps in the analyzed scientific literature. In addition, this work performed a data synthesis based on the fields described in Table 6 as follows.

- The field EF1 holds the primary/main noticed objectives from each of the 107 accepted papers. A data mining procedure on EF1 revealed a pattern in several studies according to our own main goal. As described in Table 10, seven different categories C1-C7 were identified while grouping commonly oriented studies.

Table 10. Data synthesis for the field EF1 (Table 6) extracted from all 107 accepted papers.

Category	Description	Quantity	%
C1	BESS optimization	17	16%
C2	Integration of renewable energy sourcess	13	12%
C3	Development of microgrid systems	12	11%
C4	Analysis of economic and environmental impacts	17	16%
C5	Technological advances in energy storage	12	11%
C6	Grid stability and support	14	13%
C7	Control and energy management strategies	22	21%
–	Total	107	100%

The grouping category C1 focuses on objectives related to efficiency improvement, performance, and design of BESSs. Studies in the category C1 often aim to optimize energy usage, reduce losses, and enhance system longevity. Category C2 absorbs research on incorporating renewable energy sources, such as solar and wind, into energy grids or systems. Basically, category C2 groups studies whose goal is to maximize the synergy between renewables and existing energy infrastructure. Category C3 involves the design, implementation, and enhancement of microgrid systems, which are localized energy networks capable of operating autonomously or connected to the larger grid. Category C4 is composed by studies that evaluate the cost-effectiveness and environmental consequences of energy-related technologies, including lifecycle assessments and sustainability analyses. Category C5 deals with studies focused on innovations in energy storage technologies, exploring new battery types, materials, or methods that push the boundaries of current capabilities. Category C6 is related to studies that aim to improve grid reliability and stability, particularly through technologies like BESS that support frequency regulation, voltage control, and load balancing. Finally, category C7 involves studies more focused on control system topology, discussion, feedback design, and emerging control methodologies, allowing themselves to be considered with any application from categories C1–C6.

Figure 12 highlights a diverse distribution of data, with the category of control strategies and energy management (category C7) standing out as the category with the highest concentration of articles (21%), indicating a growing interest in effective energy management methods for operating microgrids with PV-BESSs. This emphasis aligns with the global trend of digitalizing energy systems, which requires greater forecasting capacity, dynamic load response, and autonomous management of distributed energy resources (DERs). Studies such as Serban et al. (2016) [114] and Ullah et al. (2022) [111] reinforce the critical role of energy management in isolated systems and PV-BESS-based microgrids.

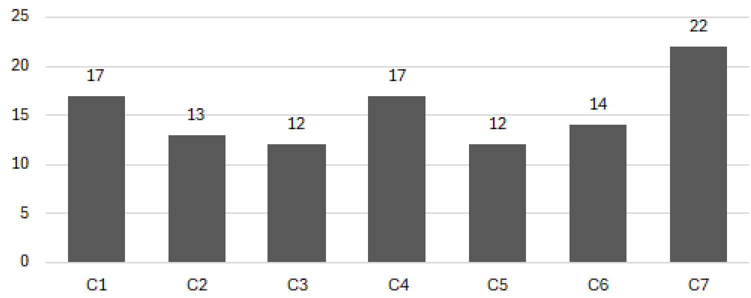

Figure 12. Distribution of accepted studies among categories extracted from the field EF1 (Table 6).

Optimization of storage systems (16%) and the analysis of economic and environmental impacts (16%) (categories C1 and C4, respectively) suggest that the techno-economic feasibility remains a limiting factor for the widespread adoption of these technologies, as discussed by Zhao et al. (2022) [105] and Gonçalves et al. (2023) [22]. The relatively homogeneous distribution of the other categories (such as grid stability C6, technological advancements C5, and renewable integration C2) points to a maturation movement in the field, where multiple aspects are being addressed in an integrated and interdependent manner.

Based on Table 10, a midpoint of quantitative distribution (value = 15.29%) demonstrates a reasonable balance among the covered topics, although some areas receive more attention than others. The most relevant topics (above the midpoint) reflect a concern with optimization (C1), impact analysis (C4), and energy system control (C7), which are crucial for the effective implementation of new technologies. On the other hand, the less-discussed topics (below the midpoint) indicate potential areas for further research development. For example, the lower representation of category C5 may suggest that, while there is interest in optimization and impact analysis, research on new technological advancements itself may be receiving less attention. Similarly, the fewer studies on category C3 may indicate that practical development and implementation of microgrids are still areas that require further exploration.

- The field EF2 exemplifies the way the authors from the 107 accepted papers aimed to achieve their main research goals. Available data on EF2 fields was analyzed to understand the predominant research strategies on LiBESS-PV systems. For this purpose, accepted studies were classified according to six categories of methods or methodologies (M1-M6) as described in Table 11.

Table 11. Data synthesis for the field EF2 (Table 6) extracted from all 107 accepted papers.

Category	Description	Quantity	%	Ref. (Studies)
M1	Case study	4	4%	[45,57,92,112]
M2	Computational simulation	49	46%	[17,18,23,44–46,49–51,54–56,58–61,64–68,71,74,75,77,78,80,81,83,86,87,89,96,97,100,104,105,108,113–116,122,123,130–133,139]
M3	Experimental or laboratory tests	6	6%	[8,53,76,85,88,126]
M4	Hybrid approach (2+ methods)	6	6%	[13,22,62,70,125,135]
M5	Literature review or longitudinal study	9	8%	[6,91,93–95,98,106,121,137]
M6	Grid stability and support	33	31%	[14–16,20,47,48,52,63,69,73,79,82,84,90,99,101–103,107,109–111,117–120,124,127–129,134,136,138]
–	Total	107	100%	(see Table 8)

Category M1 (case study) is composed of accepted studies that are based on in-depth analysis of a specific instance, organization, or event to draw conclusions and insights that may apply to similar situations. Category M2 connects studies that involve the use of computer software to create models and simulate estimated scenarios. Category M3 corresponds to a controlled investigation conducted in a laboratory setting to test hypotheses, measure variables, or observe phenomena under predefined conditions. Category M4 (hybrid approach) is related to studies that combines methodologies, such as computational simulations with laboratory experiments or theoretical analysis with case studies, to leverage the strengths of each approach and provide a more comprehensive perspective. Category M5 concentrates on research methods that involve the analysis of existing studies and the collection of data over extended periods. Finally, category M6 groups studies that rely on mathematical equations, analytical methods, or theoretical frameworks to explore concepts, predict behaviors, or explain phenomena without using computational tools.

The classification results shown in Table 11 reveal that the majority of studies (46%) used computational simulation as the main approach (M2), reinforcing the trend of using tools such as HOMER [19] and MATLAB/Simulink [141] to evaluate the techno-economic performance of PV-BESSs. On the other hand, 33 studies were classified as theoretical modeling and analysis (M6), indicating a strong presence of studies focused on mathematical formulations and conceptual analyses without experimental validation. Only six studies presented laboratory tests (M3), and another six combined testing with simulation, being classified as hybrid approaches (M4), as observed in studies such as Goncalves et al. (2023) [22] and Araujo Silva Junior et al. (2023) [23]. The small number of hybrid approaches (6%) also reinforces that most studies remain anchored in unilateral methods, lacking cross-validations between theory and practice. Systematic reviews or longitudinal studies accounted for nine publications (M5), while only four studies reported real-world applications with field data, being classified as case studies (M1), such as the work by De Morais Cavalcanti et al. (2023) [6].

Based on these presented results, it might highlight a significant gap in practical validation and field experimentation, which limits the extrapolation of findings to real operational environments. Despite advancements in detailed simulations and robust conceptual proposals, the low incidence of studies involving real-world tests and concrete implementations indicates an opportunity for future applied research. Additionally, data indicate consolidation of computational modeling as the primary methodological strategy, while integrated approaches and trials in real substations still lack greater representation in the recent literature.

- The data extraction and analysis in field EF3 aimed to identify which energy sources were used as complements to PV systems in the group of 107 studies accepted. It is important to highlight that the accounting is not exclusive per article; that is, a single study may require/incorporate multiple energy sources beyond PV or only mention PV systems as the sole source. Therefore, a direct percentage analysis based on the total number of studies is not appropriate (in the case of EF3). Nevertheless, data provide a relevant insight into the technological trends adopted to ensure the continuity of energy supply in hybrid systems, mainly focused on powering auxiliary services in high-voltage substations.

  Figure 13 indicates that among the analyzed studies, 56 use only solar energy (PV only), highlighting a significant concentration in the pursuit of purely renewable and sustainable solutions. However, 33 studies incorporated wind generation, demonstrating the consolidation of this source as the main alternative to PV generation in intermittent scenarios, as seen in the studies by Babaei et al. (2022) [14] and Husein et al. (2017) [15], with the last one suggesting that a PV–wind–diesel combination showed improvements in dynamic performance and cost reduction. The presence of diesel generators was observed in 21 studies, such as Letebele and Van Coller (2021) [20], reinforcing their traditional role as a reliable backup source, even against the ongoing energy transition.

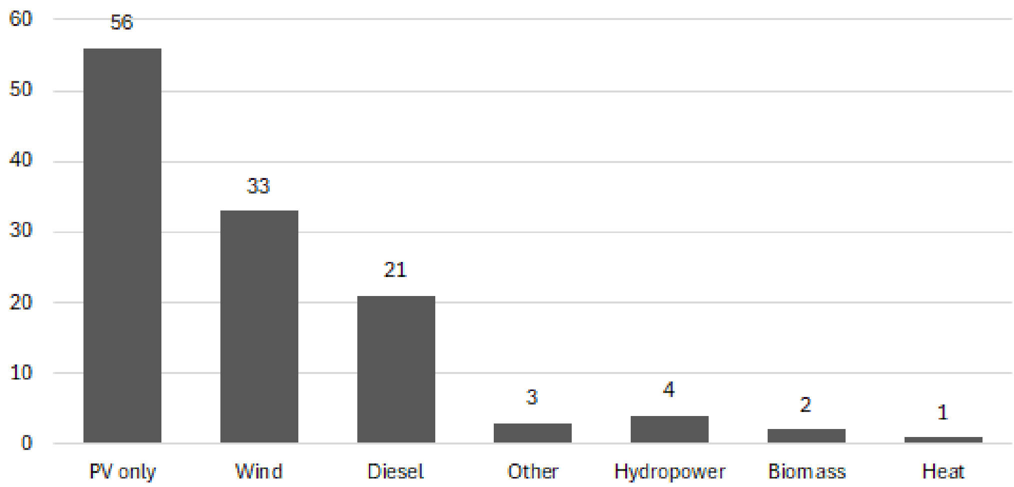

Figure 13. Different types of energy resources observed in data extracted from the field EF3 (Table 6).

Sources such as hydroelectric, biomass, and thermal energy still show low recurrence, which may be related to regional availability limitations or technological maturity. The 'Other' category, with only three occurrences, includes less conventional or emerging alternatives that do not fit traditional classifications. Among them are the use of natural gas as a complementary source to PV generation for supply stability in critical systems, as discussed by Yan et al. [123]; the application of tidal energy for power support in coastal environments, explored by Cohen (2022) [56]; and the use of hydrogen as an energy carrier complementary to battery storage, pointed out by Zhang, X.; Wei, Q.S.; Oh, B.S. [58] as a viable alternative for high-renewable-penetration scenarios. These findings reinforce that, although there is a clear preference for pure PV systems or combinations with wind and diesel, there is considerable room for expanding research into new renewable sources and their integration with BESSs, especially in off-grid contexts or autonomous substation operations, as explored by Gonçalves et al. (2023) [22] and Araujo Silva Júnior et al. (2023) [23].

- The EF4 data extraction aimed to identify the main techniques or applications associated with Li-ion BESSs combined with photovoltaic generation, as described in the 107 accepted studies. Results are presented in Table 12.

Table 12. Data synthesis for the field EF4 (Table 6) extracted from all 107 accepted papers.

Category	Application	Quantity
N1	Power source	49
N2	Ancillary (or grid) services	45
N3	Black start	18
N4	Other (not N1, N2, or N3)	15
N5	Not applicable	11

The categories N1–N5 are described as power source (N1), when the PV-BESS is used as the primary energy supply; ancillary (or grid) services (N2), which encompass applications such as frequency regulation, ramp control, and grid stability; black start (N3), where the system functions as an autonomous startup source after complete shutdowns; other (N4), for specific applications not included in the previous categories; and not applicable (N5), for conceptual studies or those that do not describe a practical application. Since a single study may be classified into more than one category, percentage analysis based on the total number of articles will not be considered, with absolute occurrence counts being prioritized.

According to Table 12, N1 (power source) has the most recurrent application (49 studies), highlighting the interest in PV-BESSs as the primary energy supply solution, especially in isolated or critical contexts. Studies such as those by De Morais Cavalcanti, M. (2023) [6] and Araujo Silva Júnior, W. (2023) [23] demonstrate the techno-economic feasibility of autonomous hybrid systems with Li-ion batteries. Ancillary services appears with 45 occurrences, demonstrating the widespread use of BESSs for grid support services. For instance, Graditi et al. (2015) [79] proposed innovative devices for interfacing renewable generators with storage, while Zhu et al. (2013) [77] analyzed control strategies for power injection smoothing. The black start application (N3), though less frequent (18 studies), proves relevant in contingency scenarios, as evidenced in Kebede et al. (2021) [13], where realistic control of microgrids in autonomous startup conditions was implemented. Applications classified as power source, black start, and ancillary services represent essential functions in the combined use of photovoltaic systems and battery storage, particularly in scenarios requiring supply continuity, operational resilience, and grid support. The 'other' category (N4), with 15 records, encompassed studies that addressed specific applications such as support for electric mobility, integration with non-conventional generators, or distinct industrial contexts, as seen in the work by Cohen et al. (2023) [56]. Finally, 11 studies were classified as 'not applicable' as they presented theoretical approaches or simulations without direct linkage to a defined practical application. These results reinforce the multifunctional nature of PV-BESSs and the diversity of scenarios analyzed in the recent literature.

- The field EF5 was considered while classifying the group of 107 accepted studies in terms of battery technology. This data extraction aims to identify the main techniques or applications associated with Li-ion BESSs combined with photovoltaic generation. Results are presented in Table 13.

Table 13. Data synthesis for the field EF5 (Table 6) extracted from all 107 accepted papers.

Category	Battery Technology	Quantity
ST1	Li-on (except $LiFePO_4$)	88
ST2	Lead-acid	25
ST3	$LiFePO_4$	19
ST4	More technologies	15
ST5	Flow	15
ST6	Supercapacitor	6

Different battery chemistries and emerging technologies were considered, grouped into the following categories: lithium iron phosphate batteries ($LiFePO_4$); Li-ion batteries (all technologies, except $LiFePO_4$); lead–acid batteries; flow batteries; supercapacitors; and batteries based on more technologies (which includes less conventional solutions or isolated occurrences). Since a single study may cite more than one storage technology, an absolute count of mentions was conducted.

Lithium-ion batteries (ST1) were the most frequently discussed technology (in terms of energy storage systems), appearing in 88 out of the 107 accepted studies. This predominance is related to their high energy density, fast response time, satisfactory lifespan, and compatibility with distributed generation applications, which justify their widespread adoption in both simulated and real scenarios. Meanwhile, 19 studies specifically mentioned the use of the $LiFePO_4$ variant (ST3), recognized for its greater thermal stability, extended lifespan, and operational safety, although it has lower energy density compared to other lithium chemistries. Lead–acid batteries (ST2), though less efficient, appeared in 25 studies, often used as a comparative reference or a lower-cost alternative, as evidenced by Merei et al. (2013) [59].

The less frequently mentioned technologies reveal the growing diversity of alternatives detected among accepted studies (a justified sample of the available literature). Flow batteries (ST5), cited in 15 studies, stand out for their scalability flexibility and separation between energy and power, making them promising for large-scale stationary applications. Supercapacitors (ST6), identified in six studies, were utilized in contexts requiring high instantaneous power and fast response, although they are limited by their low energy storage capacity. In this work, field EF5 refers to SC as an option for auxiliary energy storage devices, even though it does not exhibit (technically) the dynamic characteristics of a battery. Finally, category ST4 embraces specific approaches such as hybrid storage, advanced materials, and integration with thermal solutions. Despite the technological variety observed, few studies have conducted comprehensive experimental comparisons between different storage alternatives, indicating a significant gap for future applied research that considers aspects such as degradation, reliability, operational costs, and real-world performance.

3.3. Revisiting the Review Questions

This subsection addresses each of the review questions originally presented in Section 2.1. The following synthesis is derived from both quantitative and qualitative analyses of the 107 accepted studies, with a particular focus on the five high-relevance publications (SIF $\geq$ 4.0), as well as broader trends identified across the full dataset.

3.3.1. Highlights on Answering RQ1

"*What are the most significant scientific papers published between 2013 and 2024 that explore the use of Li-ion battery energy storage systems (LiBESS) in conjunction with PV generation as a power supply source for power stations?*"

This work identified five high-impact publications that stand out as the most assertive contributions to the field. These studies demonstrated direct application of LiBESSs integrated with PV generation for supplying alternating current (AC) to auxiliary systems in high-voltage substations. They included both simulation-based approaches and real-case studies, providing valuable insights into optimal system sizing, hybridization with other storage technologies, and reliability enhancement in critical infrastructure.

Therefore, this group of five publications collectively represent the cutting edge in integrating LiBESS-PV systems as primary or backup sources for critical substation operations. Specifically (in chronological order),

- Letebele and Van Coller (2021) [20] addressed hybrid renewable setups in switching substations.
- de Araujo Silva Júnior et al. (2023) [23] and Costa et al. (2023) [8] proposed and validated hybrid PV-BESS configurations for AC microgrids.
- De Morais Cavalcanti et al. (2023) [6] presented real-world applications above 230 kV, demonstrating feasibility in live substation environments.
- Goncalves et al. (2023) [22] explored multi-objective optimization for system sizing under contingency conditions.

As described in Table 14, this group of five high-impact publications was collected basically through three out of four data sources and seven out of nine search strings.

Both perceptions suggest a heterogeneous group of relevant studies but with similar characteristics in terms of this SLR. For example, to observe the influence of both parameters on selected and duplicated studies, the authors decided to present the data results in Table 14 taking into account the entire collection of 803 publications. As it can be noticed, there is a notable dominance of search strings S6 and S8, as well of data sources Scopus and Web of Science on the five most significant studies.

Table 14. Data sources and search strings associated with the five most significant studies.

Publication Year	Ref.	Data Source (Search Strategy, see Table 3) [4]
2021	[20]	IEEE Digital Library (S1/S6/S8)
2023	[23]	Scopus (S6/S8/S9), Web of Science (S6/S8/S9)
2023	[8]	Scopus (S1/S2/S3/S5/S6/S8), Web of Science (S1/S2/S3/S5/S6/S8)
2023	[6]	Scopus (S6), Web of Science (S6)
2023	[22]	Scopus (S6/S9), Web of Science (S6)

[4] Based on the entire collection of 803 studies, including duplicated ones.

3.3.2. Highlights on Answering RQ2

> "*Considering other energy sources beyond photovoltaic (PV) generation, what are the key battery technologies and their applications in the context of PS?*"

Following the earlier discussion based on Figure 13, this systematic review identified a list of different energy sources associated with each of the accepted studies. Although PV systems were considered as a power source in almost 52% of the accepted papers, other types of energy resources were significantly identified. Wind turbines and diesel generators also remained as the most observed types of power sources (approx. 31% and 20%, respectively).

The authors also noticed one valuable pattern among screened publications: several accepted studies addressed hybrid systems incorporating alternative renewable sources such as wind turbines, diesel generators, and, in fewer cases, tidal and hydropower. These combinations are often used in isolated or remote substations where grid access is limited. Basically, our key observations include the following:

- Diesel generators remain a widely used backup source, especially in microgrids where renewable generation intermittency needs compensation.
- Wind energy, often in conjunction with PV systems and BESSs, has been studied for autonomous systems, particularly on islands and remote areas.
- Battery technologies beyond Li-ion include
  - Lead–acid batteries, frequently used in hybrid setups due to cost and maturity.
  - Flow batteries, offering long-duration storage for larger systems but still limited in field deployment.
  - Supercapacitors, mentioned in a few studies for their fast response, though not suitable for extended backup durations.

These systems serve diverse applications such as black-start support, ancillary services, load balancing, and resilience enhancement during grid failures. The presence of hybrid energy sources and storage technologies reflects the flexibility needed to tailor solutions for different operational scenarios in power substations.

3.3.3. Highlights on Answering RQ3

> "*What are the main themes or applications addressed, and what trends suggest the most promising areas for future research?*"

The main themes addressed in the literature include microgrid configuration and control, optimal sizing of PV-BESSs, reliability analysis, and economic feasibility studies.

Common applications involve supplying power to auxiliary systems under normal and contingency conditions, as well as ensuring operational continuity during blackouts.

As presented in Table 13, storage systems based on Li-ion batteries were detected in almost 82% of accepted studies, mainly due to their dynamic characteristics like high energy density and fast response time. Less than 18% and 24% of accepted studies are based on $LiFePO_4$ and lead–acid batteries, respectively. Those numbers suggest a dominant trend in studies related to LiBESS-PV systems rather than other battery technologies.

The review also revealed several research trends and gaps that suggest promising directions for future work.

- Real-world pilot implementations of LiBESS-PV systems in live substations are still rare, despite many simulation-based studies.
- Artificial intelligence (AI)-based control systems and predictive maintenance strategies are emerging areas that could significantly improve energy management efficiency.
- AC microgrids and black-start capabilities, though critical for transmission substations, remain underexplored in empirical research.
- Cost–benefit analysis across different regulatory regions, especially in Latin America, has high potential to drive region-specific innovation.
- Comparative studies with next-generation storage technologies (e.g., sodium-ion, solid-state batteries, hydrogen storage) could offer new insights into scalable and sustainable deployments.

The authors believe that these possible research trends listed above corroborate data results previously presented in Figures 10 and 11. The concentration of recent and concurring keywords near applications related to battery energy storage systems and PV systems suggests a high demand for future research and predicts a possible growth in visionary academic and industrial interests in battery energy storage for auxiliary services, with a clear shift toward integrated and resilient system designs for the 2020–2024 period.

4. Conclusions

This systematic literature review (SLR) examined the integration of Li-ion BESSs with PV generation to supply AC power to auxiliary systems in high-voltage power substations (PSs). The review followed a robust methodology aligned with the guidelines proposed by Kitchenham et al. [24,25] and was supported by Parsifal platform [33] during review stages, from planning to data synthesis.

The primary contribution of this SLR lies in mapping and analyzing the scientific literature published between 2013 and 2024, with the goal of identifying key research works, existing gaps, and future research opportunities in the field. Through nine carefully crafted search strings applied across four major databases (IEEE Digital Library, ScienceDirect, Scopus, and Web of Science), an initial collection of 803 publications was compiled. After removing duplicates and applying defined inclusion/exclusion criteria, 107 studies were accepted and assessed using a custom study impact factor (SIF) framework.

Among these, a group of five publications achieved a high SIF score ($\geq$4.0) [6,8,20,22,23] (as detailed in Tables 8 and 9). By that, this group stood out as the most representative and assertive contributions to the application of LiBESS-PV systems in substation auxiliary services. These highly relevant studies explored topics such as hybrid storage sizing, optimal dispatch of PV-BESSs under contingency, validation through case studies, and integration into AC microgrids.

Additionally, the authors noticed that almost half of the accepted publications were related to planning and configuration studies (as presented in Figure 4). However, this specific group of studies was further classified as medium-relevance (or medium impact) studies and left aside of the core and assertive contributions expected for this SLR. Basically, selected planning and configuration studies that were published between 2013 and 2024 likely offered contributions on isolated topics such as storage devices, control methods, and projected operational scenarios (grid analysis, microgrids, etc.).

The review also revealed a significant number of studies involving other energy sources—especially diesel generators and wind turbines—used in hybrid arrangements with Li-ion and other battery technologies, including lead–acid and flow batteries and supercapacitors. These configurations are particularly relevant in off-grid and islanded systems, and they suggest the growing importance of hybrid energy systems in power station applications.

Several gaps were identified, notably the limited number of experimental studies with real-world deployments, the lack of standard performance evaluation methods, and scarce attention to regulatory, economic, and grid-compliance aspects. These gaps point to substantial research opportunities, including the following:

- Pilot-scale implementations of LiBESS-PV systems in PSs.
- Planning and operation control of LiBESS-PV systems for auxiliary services in PSs.
- Development of intelligent energy management systems based on AI to pursue an optimization of LiBESS-PV systems for auxiliary services in PSs.
- Exploration of scalable and modular microgrid solutions.
- Comparative studies with emerging storage technologies.
- Region-specific techno-economic assessments, especially in developing countries.
- Need for regulation and a higher availability of suitable devices and services, also supported by power grid operators and transmission concessionaires.

The adopted review criteria and method evaluations were instrumental in providing a comprehensive view of the field. Strengths include the methodological rigor and use of a structured protocol, while limitations involve potential publication bias, language restrictions (English only), and the inherent challenges of interpreting studies with diverse scopes. To expand the classification of screened studies and their detected relevance in terms of a systematic review, the authors believe that the study quality assessment part (as described in Sections 2.2.4 and 3.1.3) plays a key role within the protocol. Perhaps, a higher odd number of possible answers to each assessment question could result in a more homogeneous distribution of studies among the available categories of classification, suggesting a clear possible improvement in similar future systematic reviews.

Unanswered questions remain, particularly concerning the long-term performance, safety, and cost-competitiveness of LiBESS-PV systems under varied grid configurations and climatic conditions. Future research should focus on closing these gaps to enable broader and more confident adoption of renewable-based energy storage systems in the electrical infrastructure of substations.

The authors also consider that a further analysis of prospects and regulations on how Li-on batteries and PV systems are integrated across different countries and solar energy availability can lead to possible future research. In addition, the authors suggest expanding the number of source databases in future systematic reviews. For example, the Ei Compendex database [142] might be included due to its relevance in engineering.

In conclusion, this review confirms that the integration of Li-ion battery storage with PV generation offers a technically viable and promising solution for ensuring the resilience and autonomy of power station auxiliary systems. As global energy systems move toward decarbonization and increased electrification, such solutions are expected to play a critical role in modernizing electrical system infrastructure and supporting the energy transition.

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Abbreviations

The following abbreviations are used in this manuscript:

AC	Alternating current
AI	Artificial intelligence
AL	Auxiliary load
AQ	Assessment question
AS	Auxiliary service
DC	Direct current
DG	Distributed generation
DER	Distributed energy resource
IEEE	Institute of Electrical and Electronics Engineers (USA)
BESS	Battery energy storage system
LCOE	Levelized cost of energy
Li-ion	Lithium ion
LiBESSs	Li-ion battery energy storage systems
LiBESS-PV	Li-ion battery energy storage systems integrated with PV system (or systems)
NPC	Net present cost
PICOC	Population, intervention, comparison, outcome, and context
PS	Power station (or power substation)
PV	Photovoltaic (or solar)
PVT	Power voltage transformers
SC	Supercapacitor
SR	Systematic review
SIF	Study impact factor
SLR	Systematic literature review
TPL	Transmission power line
WT	Wind (turbine) generation

Appendix A. PRISMA 2020 Checklist

According to [28], PRISMA 2020 consists of a statement paper that includes a description of how the reporting guideline was developed, and presents a 27-item checklist [29]. Table A1 corresponds to the PRISMA 2020 checklist filled with information of this proposed SLR. The presented checklist was also filled in accordance with the one presented in [27].

Table A1. PRISMA 2020 checklist [27,29] of this proposed SLR.

Section and Topic	Item No.	Checklist Item	Location Where Item Is Reported
TITLE			
Title	1	Identify the report as a systematic review.	p. 2
ABSTRACT			
Abstract	2	See the PRISMA 2020 for Abstracts checklist [31].	p. 2
INTRODUCTION			
Rationale	3	Describe the rationale for the review in the context of existing knowledge.	pp. 2–3
Objectives	4	Provide an explicit statement of the objective(s) or question(s) the review addresses.	pp. 3–4
METHODS			
Eligibility criteria	5	Specify the inclusion and exclusion criteria for the review and how studies were grouped for the syntheses.	pp. 7–8
Information sources	6	Specify all databases, registers, websites, organizations, reference lists and other sources searched or consulted to identify studies. Specify the date when each source was last searched or consulted.	pp. 4–6
Search strategy	7	Present the full search strategies for all databases, registers and websites, including any filters and limits used.	pp. 4–6
Selection process	8	Specify the methods used to decide whether a study met the inclusion criteria of the review, including how many reviewers screened each record and each report retrieved, whether they worked independently, and if applicable, details of automation tools used in the process.	pp. 7–9
Data collection process	9	Specify the methods used to collect data from reports, including how many reviewers collected data from each report, whether they worked independently, any processes for obtaining or confirming data from study investigators, and if applicable, details of automation tools used in the process.	pp. 7–9
Data items	10a	List and define all outcomes for which data were sought. Specify whether all results that were compatible with each outcome domain in each study were sought (e.g., for all measures, time points, analyses), and if not, the methods used to decide which results to collect.	pp. 3–4, 9–11
	10b	List and define all other variables for which data were sought (e.g., participant and intervention characteristics, funding sources). Describe any assumptions made about any missing or unclear information.	pp. 9–11

Table A1. *Cont.*

Section and Topic	Item No.	Checklist Item	Location Where Item Is Reported
METHODS			
Study risk of bias assessment	11	Specify the methods used to assess risk of bias in the included studies, including details of the tool(s) used, how many reviewers assessed each study and whether they worked independently, and if applicable, details of automation tools used in the process.	pp. 8–9
Effect measures	12	Specify for each outcome the effect measure(s) (e.g., risk ratio, mean difference) used in the synthesis or presentation of results.	pp. 18–24
Synthesis methods	13a	Describe the processes used to decide which studies were eligible for each synthesis (e.g., tabulating the study intervention characteristics and comparing against the planned groups for each synthesis, item #5).	p. 18
	13b	Describe any methods required to prepare the data for presentation or synthesis, such as handling of missing summary statistics, or data conversions.	pp. 10, 18
	13c	Describe any methods used to tabulate or visually display results of individual studies and syntheses.	pp. 18–24
	13d	Describe any methods used to synthesize results and provide a rationale for the choice(s). If meta-analysis was performed, describe the model(s), method(s) to identify the presence and extent of statistical heterogeneity, and software package(s) used.	pp. 18–24
	13e	Describe any methods used to explore possible causes of heterogeneity among study results (e.g., subgroup analysis, meta-regression).	pp. 18–24
	13f	Describe any sensitivity analyses conducted to assess robustness of the synthesized results.	n/a
Reporting bias assessment	14	Describe any methods used to assess risk of bias due to missing results in a synthesis (arising from reporting biases).	pp. 18–24
Certainty assessment	15	Describe any methods used to assess certainty (or confidence) in the body of evidence for an outcome.	pp. 18–24
RESULTS			
Study selection	16a	Describe the results of the search and selection process, from the number of records identified in the search to the number of studies included in the review, ideally using a flow diagram.	pp. 6–7, 11–13
	16b	Cite studies that might appear to meet the inclusion criteria, but which were excluded, and explain why they were excluded.	p. 26
Study characteristics	17	Cite each included study and present its characteristics.	pp. 11–18
Risk of bias in studies	18	Present assessments of risk of bias for each included study.	pp. 7–9
Results of individual studies	19	For all outcomes, present, for each study: (a) summary statistics for each group (where appropriate) and (b) an effect estimate and its precision (e.g., confidence/credible interval), ideally using structured tables or plots.	p. 15, 25

Table A1. *Cont.*

Section and Topic	Item No.	Checklist Item	Location Where Item Is Reported
RESULTS			
Results of syntheses	20a	For each synthesis, briefly summarise the characteristics and risk of bias among contributing studies.	pp. 18–24
	20b	Present results of all statistical syntheses conducted. If meta-analysis was done, present for each the summary estimate and its precision (e.g., confidence/credible interval) and measures of statistical heterogeneity. If comparing groups, describe the direction of the effect.	pp. 18–24
	20c	Present results of all investigations of possible causes of heterogeneity among study results.	pp. 18–24
	20d	Present results of all sensitivity analyses conducted to assess the robustness of the synthesized results.	n/a
Reporting biases	21	Present assessments of risk of bias due to missing results (arising from reporting biases) for each synthesis assessed.	pp. 11–15, 25–26
Certainty of evidence	22	Present assessments of certainty (or confidence) in the body of evidence for each outcome assessed.	pp. 3, 28
DISCUSSION			
Discussion	23a	Provide a general interpretation of the results in the context of other evidence.	pp. 6–28
	23b	Discuss any limitations of the evidence included in the review.	pp. 25–28
	23c	Discuss any limitations of the review processes used.	p. 28
	23d	Discuss implications of the results for practice, policy, and future research.	pp. 25–28
OTHER INFORMATION			
Registration and protocol	24a	Provide registration information for the review, including register name and registration number, or state that the review was not registered.	p. 3
	24b	Indicate where the review protocol can be accessed, or state that a protocol was not prepared.	p. 3
	24c	Describe and explain any amendments to information provided at registration or in the protocol.	p. 3
Support	25	Describe sources of financial or non-financial support for the review, and the role of the funders or sponsors in the review.	p. 28
Competing interests	26	Declare any competing interests of review authors.	p. 28
Availability of data, code and other materials	27	Report which of the following are publicly available and where they can be found: template data collection forms; data extracted from included studies; data used for all analyses; analytic code; any other materials used in the review.	p. 28

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