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Long-term planning optimisation of sustainable energy systems: A systematic review and meta-analysis of trends, drivers, barriers, and prospects

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ABSTRACT

The long-term planning and optimisation of renewable and sustainable energy systems is indispensable for the efficient allocation of finite resources, especially in the context of the growing deployment of localised and distributed energy generation systems. These integrated resource planning endeavours primarily aim to minimise total discounted system costs while adhering to a network of interconnected technical constraints, encompassing considerations of reliability, resilience, and the integration of renewable energy sources. In this intricate landscape, the interdependence of optimisation variables that underlie sustainable energy system planning and optimisation processes underscores the critical role of advanced computational models, notably optimisation algorithms and forecasting techniques, as well as innovative business models tailored to renewable energy in the context of diverse distributed energy options. Nevertheless, despite the well-documented drivers that promote the adoption of renewable energy, an array of social, technical, economic, and regulatory barriers poses significant impediments to the realisation of optimally sized and operated renewable and sustainable energy systems. Consequently, a notable disjunction exists between the pace of advancements in enhancing the efficiency and utilisation of such systems and their practical implementation in decentralised energy initiatives. In this context, the paper undertakes a systematic and comprehensive review, synthesising existing empirical evidence concerning the long-term procurement of renewable energy resources with differing optimisation objectives and within the framework of diverse constraints. To shed light on potential strategies for mitigating the so-called "simulation-to-reality gaps" in the development of sustainable energy systems, the paper endeavours to correlate key trends in the design of renewable energy networks with critical socio-techno-economic and regulatory barriers. The review culminates in the formulation of specific recommendations aimed at surmounting these associated barriers, leveraging the pivotal drivers that bolster clean energy production and utilisation.

Abbreviations

ABCA	artificial bee colony algorithm
ACO	ant colony optimiser
AGTO	artificial gorilla troops optimiser
AI	artificial intelligence
ALO	ant lion optimiser
AMI	advanced metering infrastructure
BSA	bat search algorithm
EA	evolutionary algorithm
EaaS	energy-as-a-service
ES	evolutionary strategy
EVs	electric vehicles
GA	genetic algorithm
GBO	gradient-based optimiser
GHG	global greenhouse gas
GRASP	greedy random adaptive search procedures
HAS	harmony search algorithm
HDI	human development index

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(*continued*)

ICTs	information and communications technologies
ILS	iterated local search
IRENA	International Renewable Energy Agency
IWO	invasive weed optimisation
LA	lead-acid
Li-ion	lithium-ion
LPSP	loss of power supply probability
MFOA	moth-flame optimisation algorithm
MG	micro-grid
MILP	mixed-integer linear programming
MINLP	mixed-integer nonlinear programming
ML	machine learning
MPA	marine predator algorithm
NaS	sodium-sulfur
NIMBY	not-in-my-backyard
NiMH	nickel-metal hydride
NP-hard	non-deterministic polynomial time-hard
NSGA-II	non-dominated sorting genetic algorithm-II
O&M	operation and maintenance
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
PSO	particle swarm optimisation
PV	photovoltaic
RESs	renewable energy sources
RSESs	renewable and sustainable energy systems
SAA	simulated annealing algorithm
SDG	Sustainable Development Goal
TNPC	total net present cost
TS	tabu search
WHO	wild horse optimiser
WoS	Web of Science

1. Introduction

With approximately two-thirds of global greenhouse gas (GHG) emissions originating from energy production and utilisation, the energy sector plays a pivotal role as a significant contributor to climate change [1–3]. Consequently, the expeditious decarbonisation of the energy sector stands as an essential component of endeavours aimed at constraining global temperature increases to levels substantially below 2°C above pre-industrial levels, with a preferable target of 1.5°C, in alignment with the objectives delineated in the Paris Agreement [4,5].

In pursuit of this overarching goal, the adoption of large-scale renewable energy electrification, both within grid-connected and isolated contexts, is increasingly acknowledged as an effective strategy capable of fostering transformative synergies between increased electricity consumption and increased utilisation of renewable power generation resources [6,7].

The transition towards a reliable, cost-effective, and environmentally benign electricity system, positioned as the primary energy carrier, has primarily been facilitated by recent advancements in information and communications technologies (ICTs). Notably, advanced metering infrastructure (AMI) technologies have played a pivotal role within the evolving smart grid paradigm. Additionally, the significant declines in the cost of battery storage technologies have further underpinned this transition [8,9].

As depicted in Fig. 1, the comprehensive analysis conducted by the International Renewable Energy Agency (IRENA) in its GET2050 assessment [10] posits that a profound shift towards deep renewable energy electrification has the potential to yield a minimum GHG emissions reduction of 44% within the energy sector by 2050, when compared to a baseline scenario that adheres to a "business-as-usual" perspective, reflecting the current and projected energy policies of governments worldwide. This percentage could escalate to over 70% when considering the integration of direct applications of renewable energy, such as solar-driven heating and ventilation systems and biofuels for transportation, in conjunction with energy efficiency and conservation measures.

In this light, this research endeavours to address a critical imperative, namely, the improvement of the comprehension regarding the intricate interplay between emerging concepts and tools within the strategic planning and management of electricity networks marked by a substantial presence of renewable energy sources (RESs) – such as advanced optimisation algorithms, predictive forecasting techniques, energy efficiency interventions, along with peak shaving, load levelling, sector coupling, and energy arbitrage mechanisms [11–14]. Simultaneously, this research seeks to elucidate the principal catalysts and significant impediments driving the adoption of localised renewable and sustainable energy systems (RSESs).

More specifically, the examination of the underlying drivers and barriers linked to the large-scale integration of RSESs is poised to

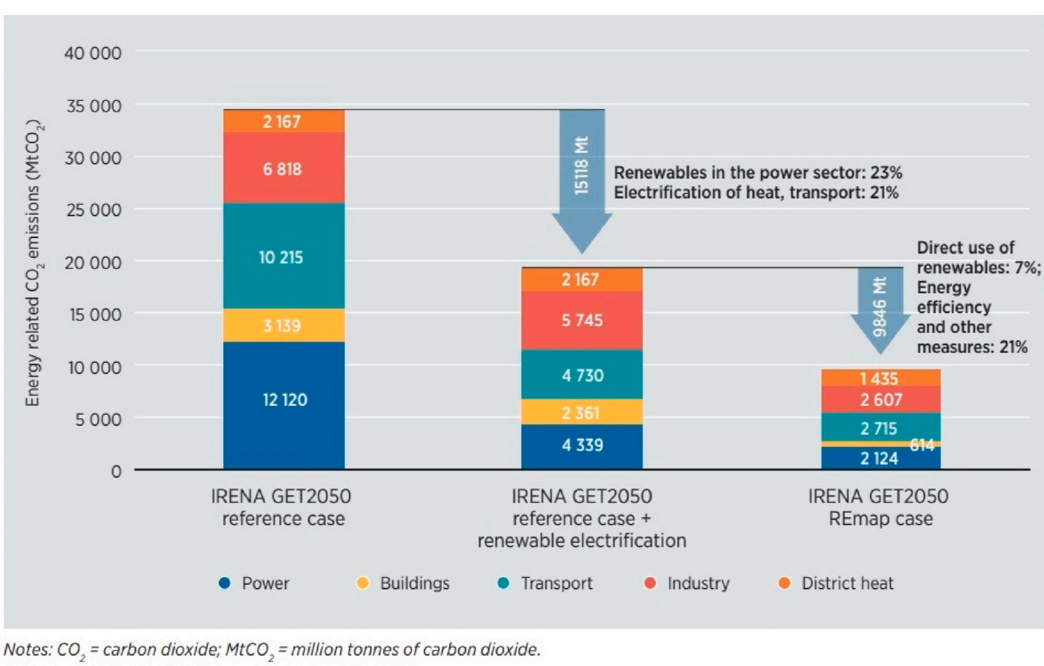


Fig. 1. Contribution of renewable electrification to global decarbonisation efforts [10].

introduce novel dimensions into the economic viability and operational efficacy of energy storage-supported grid-connected and isolated intelligent integrated renewable energy systems, particularly micro-grid (MG) systems. These levels of analysis extend beyond the conventional purview and assume critical importance in the context of the global transition toward the increased utilisation of variable RESs. This transition is a pivotal component of international efforts aimed at addressing the challenges of climate change and decentralising energy systems. Moreover, these analyses are indispensable for expediting the achievement of universal access to clean, reliable, affordable, and equitable energy resources [15–18].

1.1. Knowledge gap: previous review studies

It is widely acknowledged that comprehensive planning methodologies encompassing the examination of intricate interdependencies among various factors influencing strategic decision-making processes are instrumental in achieving optimal resource utilisation while maintaining the desired quality of service standards [19–21].

However, it is imperative to underscore a critical limitation prevailing in numerous existing optimisation approaches for renewable energy system planning. These approaches predominantly revolve around economic considerations and often neglect the imperative of adopting a multi-dimensional approach. Such an approach would consider the inherent value assigned by the target community to factors such as affordability, reliability, resilience, security, and the sustainability of the energy supply. This oversight results in a disconnection between the simulation outcomes and the practical realities on the ground [22–24].

Within this framework, there exists a pressing necessity to elevate the depth and granularity of numeric energy planning simulations, which rely on mathematical models, to a level where they closely mirror real-world dynamics [25,26]. Concurrently, there arises an imperative to craft the design of RSESs in a manner that optimises the collective advantages based upon the desires of consumers and communities while mitigating any adverse impacts on the utility grid (in cases of grid-connected systems).

To this end, it becomes essential to incorporate and harmonise pertinent social, economic, technical, and regulatory dimensions into the decision-making processes associated with energy planning. This concerted effort is directed towards the realisation of energy solutions that are unequivocally customer-centric [27,28].

In this context, delving into the intricate interplay among various parameters – such as technology attributes and expenses, patterns of load growth and their respective sectoral origins, region-specific configurations and demographic factors, geographical scope, and other relevant variables – is pivotal for fostering more enlightened decision-making within the context of business case analyses. Nonetheless, this study introduces supplementary complexities into the process of crafting the methodology, primarily in the realm of mathematical modelling. To a somewhat lesser extent, these complexities also extend to the numerical simulation of the developed mathematical models [29,30].

Numerous scholarly works have concentrated on the review of optimisation techniques in the realm of energy planning, specifically tailored to RSESs [9,31–35]. For instance, in a recent study, Akbas et al. [36] conducted a comprehensive examination of optimisation-based methodologies pertaining to rural electrification. Other research efforts have provided valuable insights by offering overviews of the literature concerning energy infrastructure integration. Notably, Rehman et al. [37] conducted a review of planning studies encompassing the integration of pumped-hydro energy storage systems. Similarly, Zhao et al. [38] and Diaz-Gonzalez et al. [39] concentrated on scrutinising energy storage systems suitable for supporting the integration of wind power and the associated optimisation methods. Hemmati and Saboori [40] contributed a review centred on planning approaches designed for the integration of hybrid energy storage systems.

Furthermore, Eyisi et al. [41] and Hatziargyriou et al. [42] critically assessed mathematical models devised for the optimisation of grid-connected energy storage systems. Extending the scope, Ringkjøb et al. [43] conducted comprehensive reviews of the existing analytical tools found in both academic and industrial domains, specifically concerning the optimal sizing and placement of energy storage systems within distribution networks. In a narrower investigation, Haas et al. [44] conducted an extensive review of 90 journal publications exploring the role of energy storage systems in enhancing the technical feasibility and economic viability of capacity expansion planning exercises.

Additionally, there exists a cluster of review studies that specifically focus on the long-term planning optimisation of remote, stand-alone RSESs [45–48]. To illustrate, in a recent study, Ridha et al. [49] conducted a comprehensive survey of multi-objective optimisation methodologies tailored to the capacity planning of off-grid solar photovoltaic (PV) systems. Similarly, Rojas-Zerpa and Yusta [50] devoted their research efforts to the examination of studies centred on the multi-criteria optimal planning of non-grid-connected RSESs situated in isolated regions. Furthermore, Siddaiah and Saini [51] undertook an investigation into various configurations and topologies employed in RSESs, with a specific emphasis on grid-isolated systems.

The integration of demand-side flexibility resources, with a specific focus on demand response programs, has also garnered increasing attention within the literature on energy system planning [52–55]. In this vein, Clauβ et al. [56] conducted a comparative review, encompassing 45 publications, that delves into advanced control optimisation methods aimed at harnessing the potential of demand-side flexibility resources, thereby enhancing the economic viability of RSESs.

Expanding on this theme, Sharifi et al. [57] explored the role of optimisation-driven demand-side management frameworks, positioned as a distributed energy resource option. These frameworks are instrumental in bolstering the economic feasibility of localised grid-connected RSESs through the implementation of effective market-based mechanisms.

In a similar vein, Mohseni et al. [58] undertook a comprehensive review and synthetic analysis of 252 studies, examining the incorporation of demand response strategies into energy planning optimisation under conditions of uncertainty.

Moreover, Esther and Kumar [59] presented a survey encompassing optimisation-based residential demand-side management approaches, shedding light on their potential significance in providing a flexibility option essential for the cost-effective integration of a high proportion of variable RESs. However, it is emphasised that the overall significance of these approaches hinges on the implementation of well-coordinated strategies and frameworks.

Based on the aforementioned considerations, there is a gap in the literature concerning comprehensive literature reviews that specifically examine the interrelationships among various foundational parameters and the essential criteria for the design of sustainable energy systems. Put differently, the prevailing body of literature reviews has typically neglected the critical inclusion of social and regulatory perspectives in the realm of energy system optimisation, predominantly concentrating on technical aspects. To elaborate further, there has been relatively limited dedication of efforts to explore the optimisation challenges in energy planning within a more unified and cohesive framework. Such a framework would seamlessly integrate well-defined socio-techno-economic and regulatory insights, resulting in enhanced levels of consistency, comprehensiveness, and model compatibility and adaptability. This, in turn, would enable the optimisation models to more accurately represent real-world conditions and dynamics [23,60].

In conclusion, this review is motivated by demonstrating the pressing need for a more holistic and integrative approach to energy system planning and optimisation. While existing literature has made significant strides in addressing the economic and technical facets of sustainable energy systems, it has often fallen short in embracing the broader perspective that encompasses social and regulatory dimensions. The discussions have predominantly centred on key characteristics such as decentralisation and adequacy, leaving gaps in the exploration of how demographics, structures, and applications intersect with these elements.

More broadly, there exists a compelling need to introduce a new layer of insight and perspective into the strategic decision-making processes of energy system design. This entails a comprehensive understanding of the intricate relationships between different parameters and the multifaceted requirements of sustainable energy systems.

Importantly, to bridge these gaps and propel sustainable energy solutions into the mainstream, decision-makers must be informed by the diverse strands of the literature and equipped with flexibility in their business cases. This flexibility will be essential in navigating the complexities further complicating the energy planning optimisation area, particularly as it pertains to the incorporation of demand-side resources and the evolving regulatory landscape. In this evolving landscape, holistic approaches are required for the optimal use of energy resources and to unlock the full potential of renewable energy storage systems.

1.2. Aim and objectives

The overarching aim of this comprehensive review is to provide a multi-dimensional understanding of the intricacies inherent in the long-term strategic planning, operation, optimisation, and asset allocation processes related to RSESs. This understanding is paramount in addressing the fundamental challenges posed by more holistic and integrated approaches to energy planning. To this end, the review embarks on a systematic and all-encompassing examination of the pertinent literature. Accordingly, it seeks to elucidate the intertwined nature of these processes and the nuanced interactions between the underlying variables, thereby shedding light on the socio-techno-economic and regulatory drivers, barriers, and consequential implications.

The review paper makes several key contributions:

1. It provides a comprehensive review that goes beyond traditional boundaries in energy planning optimisation studies. This review integrates analyses at the social and regulatory levels, offering a detailed exploration of the complex relationships, their interconnections, and the underlying interdependencies.
2. It introduces an innovative classification framework for energy planning and dispatch optimisation problems. This framework is based on a thorough categorisation of studies according to various essential criteria. These criteria include the specific objectives of the addressed problems, the primary constraints faced, the methodologies used for solutions, the adoption of different business models, and the various components, scales, and extensive geographical service territories covered in these studies. This structured classification system serves as an effective tool for navigating the diverse landscape of RSES planning optimisation.
3. It identifies and highlights significant research gaps and research questions that are crucial for the widespread deployment of RSESs. This aspect is particularly important in the context of data-driven decision-making efforts, which must contend with a growing array of sources contributing to heterogeneity in valuations.

In summary, this systematic literature review, grounded in a meta-analysis approach, aspires to not only identify and classify existing research but also to provide a coherent, cohesive, and comprehensive perspective on the multi-dimensional landscape of RSES planning and operation optimisation. In this context, it seeks to bridge the heterogeneity that pervades the field, fostering a more coordinated and holistic understanding. The ultimate goal is to expand the boundaries of knowledge, enabling the development of more informed and efficacious strategies in sustainable energy system design, allocation, and operation.

1.3. Organisation

The paper is structured as follows. Section 2 outlines the systematic literature review and meta-analysis methodology employed in this study. Section 3 presents the results of the literature review, accompanied by a thematic classification and synthetic analysis of the broader relevant literature. Section 4 examines the barriers to the deployment of local renewable energy solutions, whereas Section 5 focuses on the associated drivers. Section 6 discusses the optimal system configurations studied and equipment capacity planning problems formulated in the literature. Section 7 delves into context-specific best practices and provides recommendations for future research directions. Finally, Section 8 offers a conclusion, where the main findings and limitations of the study are discussed.

2. Review methodology

2.1. Search strategy and selection of papers

The review methodology employed in this study entailed a systematic exploration of the existing literature, with Thomson Reuters's Web of Science (WoS) online database serving as the primary information source. Within the WoS literature database, a comprehensive search was conducted, encompassing the title, abstract, and keywords fields of relevant papers. The methodology for this review was inspired by the approach initially proposed by Glock and Hochrein [61]. Specifically, the review method was structured into three key phases:

(i) Identification of relevant publications: This initial phase involved the meticulous search for selected publication types through the application of predefined search queries within the chosen literature database.
(ii) Relevance assessment: Following the compilation of the identified publications, a rigorous assessment of their relevance was undertaken. This process commenced with a thorough examination of titles, abstracts, and keywords. Subsequently, full papers deemed suitable for inclusion underwent a detailed evaluation.
(iii) Snowballing technique for enhanced coverage: To maximise the comprehensiveness of the review, a snowballing technique was employed. This entailed a meticulous examination of the reference sections of articles already included in the review, aiming to identify and incorporate articles that had subsequently cited these selected papers. In this context, Google Scholar served as the primary citation tracking database.

By adhering to this multifaceted methodology, the review seeks to provide a comprehensive and robust analysis of the pertinent literature, ensuring that a broad and diverse array of relevant research contributions are considered.

To identify pertinent publications, a meticulous search strategy was devised. The search criteria involved the use of the term "energy planning" in conjunction with an array of keywords associated with optimisation, technical considerations, economic factors, as well as social and regulatory dimensions, as outlined in Table 1. Moreover, the scope of this review was explicitly limited to English-language peer-reviewed journal articles and conference papers. The time frame for inclusion encompassed all papers published between January 2000 and September 2023. This rigorous approach to search criteria and publication selection ensured the focus on a comprehensive and up-to-date body of literature relevant to the study's objectives.

Additionally, it was deemed essential to make a distinct consideration regarding studies conducted using open-access or commercial off-the-shelf energy planning optimisation software packages, which were deliberately excluded from the scope of this review. This decision stemmed from the inherent limitations observed in software packages tailored for energy planning optimisation, particularly in terms of

Table 1
Illustration of the search strategy, including the combination of keywords, used in the literature search process.

Item	Selection
Strings of search terms	("energy planning" OR "energy scheduling"); AND a) **optimisation** ("optim*" OR "objective" OR "criteria"); OR b) **technical** ("technic*" OR "technol*" OR "feasibility"); OR c) **economics** ("least-cost" OR "cost-minimal"); OR d) **social** ("soci*" OR "community"); OR e) **regulatory** ("regul*" OR "tariff" OR "administer*")
Fields searched	Title, abstract, and keywords
Document type	Peer-reviewed journal and conference papers
Period explored	January 2000 to September 2023
Database	Web of Science

technical intricacy and flexibility.

However, readers seeking insights into these excluded publications can refer to the following resources for comprehensive categorisation and documentation of community-scale-applicable energy planning tools [62], critical analysis of renewable energy system modelling tools with a focus on their underlying optimisation objectives [63], a comprehensive review of large-scale energy planning tools [64], or characteristic-based classification and cataloguing of available tools with discussions of associated trends [65].

In the context of reviews focused primarily on tools and software packages designed for the optimal sizing of RSESs, these tools can be broadly categorised into two distinct classes. The first category adopts a full-factorial approach to address MG sizing challenges. Notable tools within this category include the original HOMER and RETScreen software packages. However, it is essential to acknowledge that these tools encounter limitations related to the so-called 'combinatorial explosion' when dealing with a significant number of candidate technologies or when striving to enhance the fidelity of the decision space [66].

The second category of tools for assessing the techno-economic feasibility of MGs employs simplified exact mathematical optimisation algorithms. Prominent software packages in this class encompass HOMER Pro, Hybrid2, iHOGA, REOpt, and DER-CAM. As expected, these software packages share analogous limitations with the analytical solution approaches previously mentioned in the context of MG planning [66].

2.2. Research questions

The exploration of the literature was driven by a set of competitively formulated research questions, which played a pivotal role in guiding the review process. These research questions are outlined as follows:

RQ1. What are the prevailing trends in the long-term strategic planning of RSESs concerning optimisation algorithms and the key constraints involved?

RQ2. What are the primary catalysts propelling the deployment of RSESs, and conversely, what are the principal barriers encountered in various contextual settings?

RQ3. What are the significant socio-techno-economic-regulatory implications stemming from different business models applied to RSESs?

These overarching research questions not only facilitated the comprehensive review of relevant literature but also served as the foundation for content mapping. Moreover, they played a pivotal role in identifying broader trends and advancements within the domain of RSESs planning optimisation literature.

3. Results and discussion

3.1. Identification of the eligible records

Following a preliminary evaluation of a total of 17,091 articles, conducted through an assessment of their titles, abstracts, and indexing terms, a refined selection process identified 535 papers as eligible for an in-depth and comprehensive review. These selected papers were subsequently categorised based on several key criteria, encompassing system configurations and integrated technologies, optimisation approaches and objectives, load types, study areas, and scales of investigation.

For a more detailed representation of the systematic literature search process, the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses)[1] framework was employed. As depicted in Fig. 2, the PRISMA flow diagram illustrates the sequential flow of information through distinct phases of the systematic review. It provides a clear depiction of the numbers of identified records, those included and excluded, and the pertinent reasons underlying the exclusions. This visual representation enhances the transparency and rigour of the review process, ensuring a robust and well-structured approach to synthesising the literature.

As illustrated in Fig. 2, the systematic literature search process commenced with the identification of 17,091 records that exhibited the potential to align with the initial inclusion criteria, considering the extended search terms. This number expanded to 17,363 documents following the inclusion of articles discovered through the snowballing technique (n = 272). During the subsequent stages of the review process, a total of 10,045 records were excluded.

The exclusionary steps encompassed several facets, including the removal of duplicate records (n = 9,054), records marked as ineligible aided by dedicated automation tools (n = 509), and the application of various other exclusion criteria (n = 482). These additional exclusion factors encompassed records published in languages other than English, those incorrectly categorised in terms of publication type, and those deemed irrelevant for the review's objectives.

Following these initial steps, a refined set of 7,318 papers advanced to the screening stage, where the selection criteria were applied meticulously to assess their titles, abstracts, and indexing terms. Within this screening phase, a further 3,631 papers were excluded due to more detailed exclusionary factors. These factors include:

(i) Papers exclusively focused on theoretical or conceptual dimensions (n = 841).
(ii) Papers concentrating solely on traditional bulk power systems (n = 758).
(iii) Papers primarily centred on energy efficiency and/or conservation aspects (n = 653).
(iv) Papers primarily emphasising ecological sustainability over decarbonisation of the energy system (n = 529).
(v) Papers explicitly aimed at deriving or synthesising load demand profiles (n = 441).
(vi) Papers conducted using dedicated open-access or commercial off-the-shelf energy planning tools (n = 308).
(vii) Papers categorised incorrectly in terms of publication type (n = 101).

Out of the refined set, a total of 3,687 papers underwent eligibility evaluation based on their full-text content. The outcome of this comprehensive evaluation process led to the exclusion of 3,152 full-text papers for various reasons, which encompassed:

[1] PRISMA is an evidence-based minimum set of items for reporting in systematic reviews and meta-analyses. For more information see http://www.prisma-statement.org/.

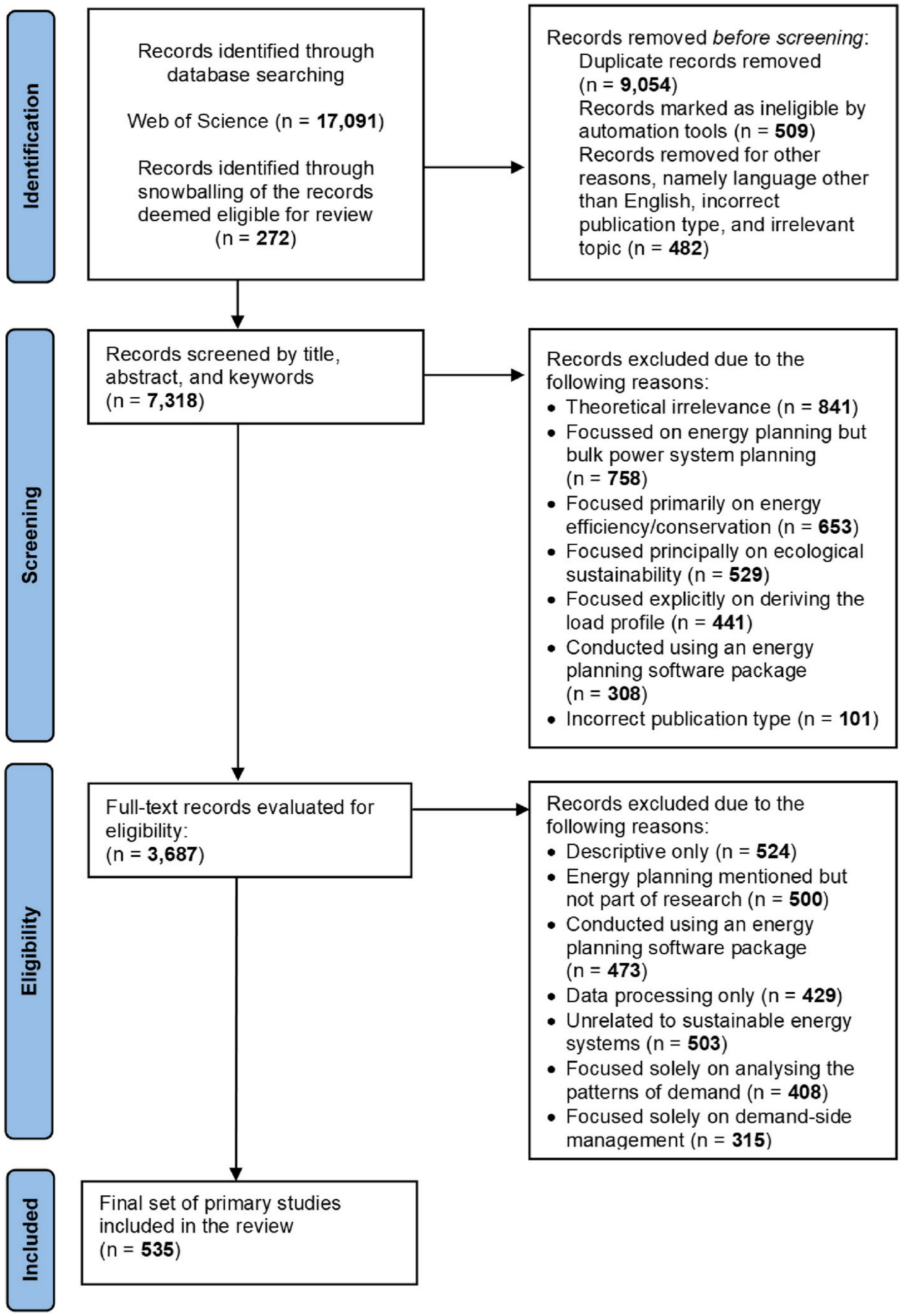


Fig. 2. PRISMA flow diagram of the systematic literature review process.

(i) Papers characterised solely by a descriptive nature (n = 524).
(ii) Papers making mention of energy planning and/or energy scheduling but not constituting research contributions (n = 500).
(iii) Papers reliant on tailored software packages (n = 473).
(iv) Papers primarily focused on data processing without substantive engagement in energy system topics (n = 429).
(v) Papers lacking specification of an energy system (n = 503).
(vi) Papers explicitly concentrating on patterns and trends related to energy demand (n = 408).
(vii) Papers exploring demand-side management schemes within contexts unrelated to energy planning (n = 315).

As a result of this rigorous evaluation, a total of 535 papers were deemed eligible for inclusion and subsequently advanced to the thematic characterisation and meta-analysis phases. These subsequent phases delve into the statistical information and associated trends found within the selected papers (for detailed information on all included papers, please refer to Table SM1 in the Supplementary Material accompanying the paper).

3.2. *Classification of focus factors*

Within the collection of 535 selected studies, a diverse range of focus factors emerged. All these studies employed specially crafted analytical study designs tailored to address the complex energy planning and scheduling challenges. These designs were instrumental in quantifying the intricate relationships between various socio-techno-economic and regulatory variables, thereby shedding light on their relative significance and interplay. Notably, none of the studies within the final set were of a descriptive nature, as this aligns with the expectations for a review study that emphasises the analysis of socio-techno-economic and regulatory implications in energy planning optimisation.

However, despite the overarching focus of this review study on analysing the socio-techno-economic and regulatory dimensions of energy planning optimisation, it is worth noting that not all the included studies were equally adept at generating novel and pertinent insights. The diversity in the depth and breadth of insights across the selected studies underscores the multifaceted nature of the field and the varying degrees of contribution to the overall body of knowledge.

Fig. 3 presents a Venn diagram depicting the distribution of studies among the four primary objectives pertinent to the decision-making processes. The diagram illuminates a disproportionate distribution of focus among these four key aspects. Notably, the financial and technical dimensions have garnered the largest share of attention within the body of research. In contrast, a comparatively limited emphasis has been placed on the exploration of social and regulatory factors in the context of energy planning and asset allocation processes. This observation underscores the need for greater attention to these often-understudied dimensions within the broader landscape of distributed energy planning literature.

Furthermore, a significant portion of the reviewed studies primarily pertains to economic viability modelling[2] (n = [441]), followed closely by those focusing on technical feasibility modelling[3] (n = [412]). In contrast, a relatively smaller body of literature delves into the realms of social acceptability (n = [37])[4] and regulatory aspects (n = [33]). It is worth noting that some studies have attempted to concurrently explore two of these four thematic areas, as evident in the intersection areas of the Venn diagram.[5] Notably, the most prevalent combination within the literature addresses the interplay between economic viability and technical feasibility modelling. However, it is noteworthy that the systematic review did not identify any studies that comprehensively address at least three of the overarching energy planning problem types together.

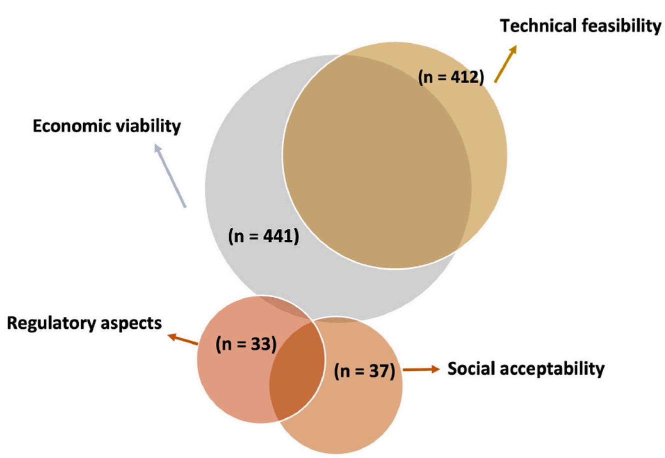


Fig. 3. Distribution of the eligible articles for inclusion in the review into the mainstream problem categories.

In conclusion, the extensive analysis of the literature reveals a distinct imbalance in the emphasis placed on various facets of energy planning optimisation within the context of MGs. While economic and technical dimensions have received substantial attention, the relatively limited focus on social acceptability and regulatory aspects underscores the potential for higher simulation-to-reality gaps. This disparity in attention could pose challenges during implementation, potentially leading to sub-optimal designs or necessitating costly redesigns and re-engineering efforts. To address these gaps, it is imperative to consider a more holistic approach that integrates case studies, explores diverse scales, and recognises the interconnected dynamics of socio-techno-economic and regulatory factors, fostering a more comprehensive understanding of local energy system planning optimisation.

3.3. Temporal development

Fig. 4 provides a summary of the literature records spanning the period from January 2000 to September 2023. The figure illustrates a surge in interest regarding the long-term strategic planning and operational scheduling of localised sustainable energy systems, particularly from 2013 to the present. Notably, the year 2018 witnessed a pronounced upswing in this trajectory. This notable increase can, in part, be attributed to the adoption of the United Nations' 2030 Agenda in 2015, with a specific focus on Sustainable Development Goal (SDG) 7, which aims to ensure universal access to reliable, affordable, clean, and modern energy. It becomes evident that advanced strategic energy planning optimisation methods are deemed essential to meet the diverse and at times conflicting objectives integral to the attainment of SDG 7.

Consistent with the analysis presented in Sections 3.1 and 3.2, Fig. 5 offers a comprehensive breakdown of the temporal trends within each overarching theme found in the reviewed literature. These themes align with the criteria and constraints encompassing technical, financial, social, and regulatory aspects. The chronological evolution of these considerations within the realm of long-term strategic energy planning studies mirrors the broader trajectory of the literature. There is a discernible shift towards an increasingly pronounced emphasis on the techno-economic facets of energy planning. However, this focus appears to come at the expense of the social desirability dimensions, regulatory factors, and business models, which are pivotal elements that can significantly impact the successful deployment of localised RSESs.

The comparative trends delineated in Fig. 5 underscore the previously highlighted disproportionate allocation of attention to the four primary problem types within the localised distributed energy planning literature. Notably, while the distribution of studies dedicated to the regulatory and social dimensions of strategic energy planning has exhibited relative stability up to 2015 and a reduction during the period 2016–2023, there has been a marked surge in publications addressing the economic viability, technical feasibility, and optimisation areas, particularly in the period spanning 2018–2023.[6]

[2] Note that the studies purely addressing the optimisation of the combination of the capacities and/or scheduling of the candidate technologies in the candidate pool (without detailed electrical engineering considerations, such as voltage and frequency control) fall squarely in the realm of economic viability modelling.

[3] Note that for the purposes of this review study, technical feasibility evaluation refers to specific and accurate power system planning with in-depth electrical engineering simulations and objectives such as determining the maximum local renewable generation a MG could support and the limits on export and import (in grid-connected MGs). In this setting, a considerable body of the literature that falls only under the economic viability modelling category, despite claiming to be focused on the techno-economic modelling.

[4] The regulatory frameworks for MGs are premised on the legal and administrative aspects of localised generation and supply of electricity, with different legal entities operating the network cooperatively considering the associated retail aspects.

[5] Note that the studies that fall in the intersection areas of the Venn diagram do not necessarily co-optimise the relevant criteria (technical, financial, social, or regulatory), but rather in most cases seek to integrate them in a constrained single-objective optimisation problem or a double-loop nested optimisation problem.

[6] Note that given the existence of partial results for the year 2023, the number of relevant studies was upscaled assuming the same publication rate for the remaining months of 2023.

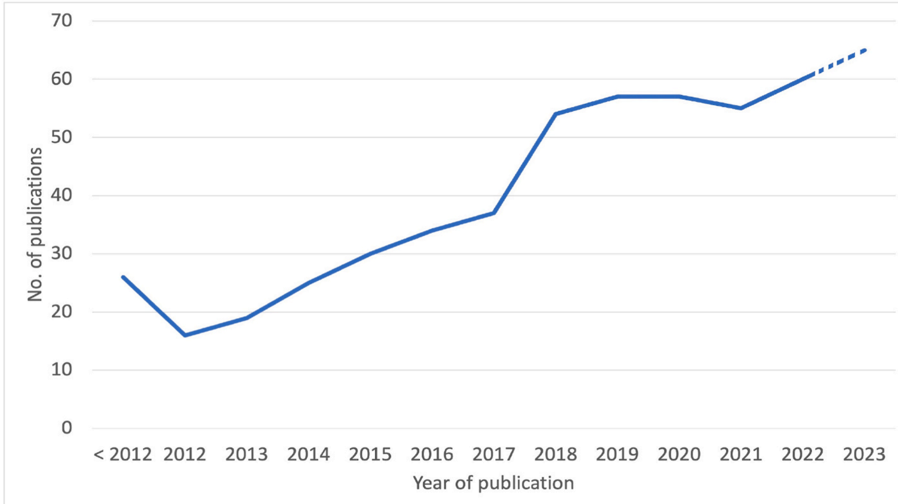


Fig. 4. Distribution of included papers into year of publication.

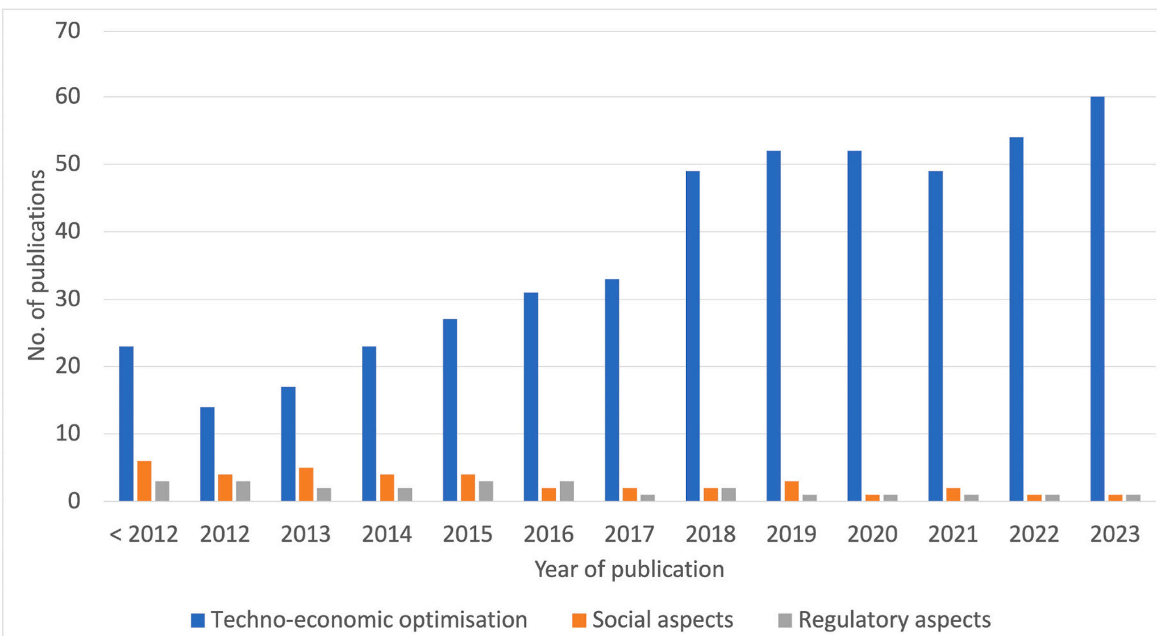


Fig. 5. Number of reviewed publications per year that fall under each theme.

3.4. *Geographical scale of case studies*

The geographical scale of case studies featured in the reviewed literature offers valuable insights into the context-specific considerations surrounding the long-term strategic planning of localised RSESs. These case studies, while diverse in their scope, can be broadly categorised into three predominant scales, as follows:

3.4.1. *Local or community-scale studies*

- These case studies focus on MGs and localised energy systems serving a small, often community-level, geographical area.
- They are instrumental in understanding the intricacies of energy planning within specific neighbourhoods, villages, or localised communities.
- Local-scale studies often provide valuable insights into the social dynamics, economic feasibility, and technical feasibility of RSESs tailored to a specific community's needs.

3.4.2. *Regional or municipal-scale studies*

- At this scale, case studies expand their scope to encompass a broader region, municipality or council.
- They offer a middle-ground perspective, examining the interplay of localised energy planning within a larger administrative boundary.
- Regional-scale studies are particularly informative in assessing the scalability of RSESs, considering factors such as grid integration, regulatory frameworks, and energy demand patterns within a defined region.

3.4.3. National or cross-border studies

- These case studies extend their purview to a national or cross-border scale, examining energy planning optimisation across an entire nation or between multiple countries.
- They provide a macro-level perspective, considering overarching policy frameworks, energy infrastructure interconnections, and transnational collaboration in sustainable energy planning.
- National-scale studies contribute to a comprehensive understanding of the macroeconomic impacts, energy security considerations, and cross-border energy trade dynamics associated with RSES deployment.

The choice of geographical scale in case studies often depends on the research objectives, available resources, and the specific questions being addressed. While local-scale studies offer granular insights into community-level energy planning, regional and national-scale studies provide a broader context for evaluating the socioeconomic and regulatory implications of RSESs. Overall, the inclusion of case studies across these geographical scales enriches the literature by offering a diverse array of perspectives on long-term strategic energy planning optimisation.

4. Barriers to the deployment of sustainable energy systems

The systematic review of the relevant literature has identified several critical barriers that impede the rapid deployment of optimally planned localised RSESs. These barriers can be broadly categorised into four main dimensions, namely: technical, economic, social, and regulatory, aligning with the major thematic areas prevalent in the literature. Among these, socio-techno-economic and regulatory barriers emerge as the primary hindrances obstructing the widespread adoption of decentralised energy systems, especially those integrating a substantial share of distributed energy resources at a significant scale.

The following sections provide a detailed discussion of the relevant barriers and their sub-categories, with a particular focus on technical barriers due to their specific relevance to the scope of this review study.

4.1. Technical barriers

The primary technical obstacles to renewable energy project development encompass limited infrastructure maturity, complexities associated with energy storage, absence of onsite operation and maintenance (O&M) resources, and suboptimal equipment performance under real-world conditions [67].

4.1.1. Non-dispatchable renewable resources

One of the significant challenges entailed in the integration of RESs lies in the inherent variability characterising power generation [68]. Notably, technologies such as solar PV and wind turbines are contingent upon specific day-to-day and seasonal meteorological conditions, thereby directly influencing the sizing of integrated storage systems – a crucial element for enhanced dispatchability. The uncertainties inherent in forecasts of non-dispatchable power outputs can potentially lead to over-dimensioned generation components, consequently amplifying the total discounted cost associated with MGs. In the context of oversized solar PV installations, this scenario further introduces increased complexities in voltage control [69]. Moreover, as the system components expand in scale, the complexity escalates due to the interplay among uncertain factors, particularly attributable to the synergistic interactions between different RESs [70].

The review of pertinent literature further discerns that solar PV and wind resources stand out as the preferred generation technologies for facilitating and propagating clean energy through the widespread adoption of MGs. This is illustrated in Fig. 6, which delineates wind generation capacity as a proportion of the overall electricity generation within the energy mix of select countries [71]. Considering the aforementioned volatility in power outputs associated with solar PV and wind turbine technologies, the imperative arises for the implementation of more advanced control systems. These systems are indispensable for

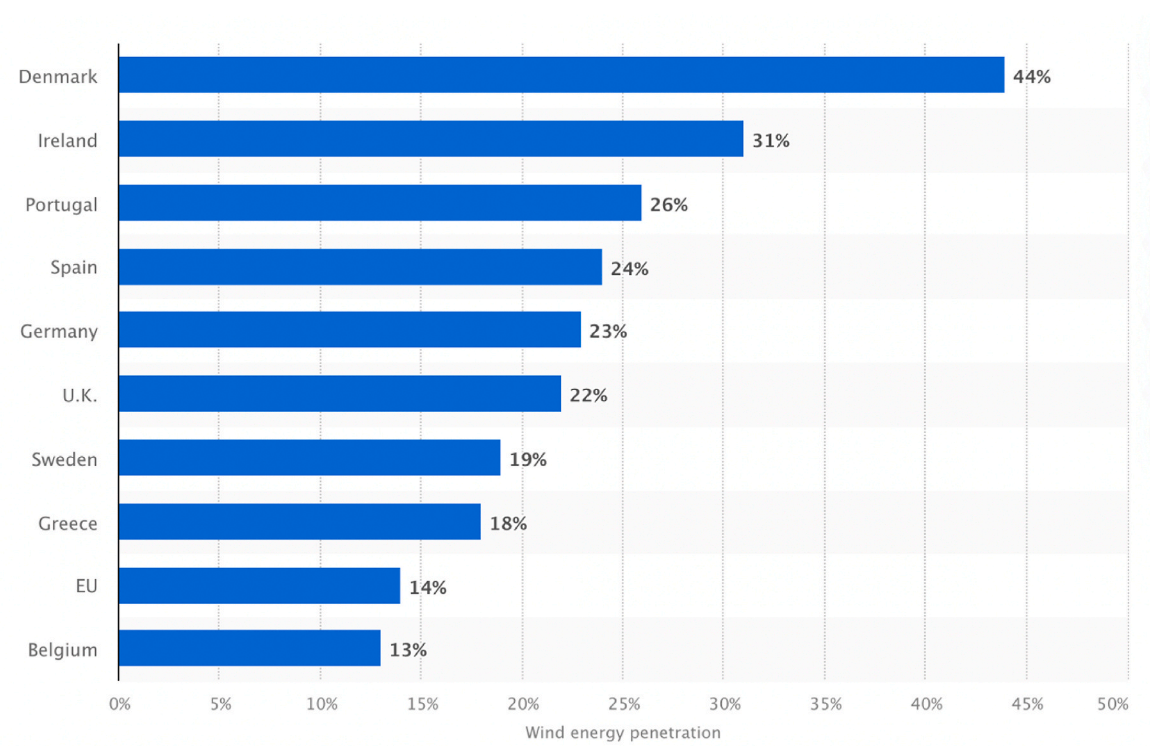


Fig. 6. Penetration of wind turbines in selected countries' energy mix [71].

achieving cost-effective and reliable means to meet the energy demands efficiently [72].

4.1.2. Dispatchable renewable resources

The relevant literature under review has also deliberated upon the technical intricacies linked with dispatchable RESs, with notable attention directed towards biopower generation, albeit to a lesser extent compared to non-dispatchable resources. Specifically, the review brings to light several noteworthy challenges associated with biopower generation, encompassing concerns regarding GHG emissions, the assurance of an ample supply of feedstock, and the comparatively higher generation costs vis-à-vis fossil fuel-based power plants and non-dispatchable renewables [73]. Furthermore, for large-scale biopower projects, the levelised cost of energy escalates in tandem with the capacity, and consequently, the distance of the station from load consumption points due to air quality considerations. Additionally, an excess of moisture in biomass pellets could engender reduced electricity generation efficiency in large-scale biopower plants, as it leads to decreased thermal efficiency resulting from excessive heat absorption. Conversely, if biomass resources lose excess moisture, this could entail supplementary production costs due to decreased efficiencies [74]. Hence, ensuring the optimal moisture content in biomass resources for efficient power generation emerges as a challenging task. This, in turn, introduces an element of uncertainty in the power outputs of biopower plants, rendering probabilistic quantification a challenging task. Importantly, the presence of unquantified uncertainty factors can potentially induce unforeseen voltage fluctuations, particularly within the context of a MG scale [75].

4.1.3. Energy storage complexities

The review has also unveiled notable deficiencies in the existing standards and guidelines pertaining to the integration of energy storage, which bear paramount significance for ensuring the reliable operation of highly renewable MGs. These inadequacies have posed hindrances to the widespread commercialisation of pioneering storage technologies, thereby yielding direct adverse repercussions for the large-scale incorporation of variable renewables [76]. This holds particularly true concerning the pivotal role played by energy storage systems in the effective management of energy flow – from generation to consumption – in a manner that preserves power quality [77].

Furthermore, the review substantiates that battery storage stands as the most favoured storage technology, not solely confined to remote, off-grid applications that bolster variable renewables, but also extending its dominance to grid-connected systems participating in deregulated electricity markets and employing advanced energy arbitrage mechanisms [78]. It is noteworthy to underscore that battery storage technologies have widely assumed the role of replacing diesel generators in the previous generation of MGs, widely recognised as hybrid renewable energy systems [79].

The literature review also discerns that battery storage is typically characterised by fixed energy and power capacities per unit of storage under consideration, as well as in adherence to the predetermined MG topology [80]. During the capacity planning and design phases, other salient characteristics of battery storage that are considered encompass factors such as efficiency, operating temperature, depth of charge and discharge, lifespan, and energy density [81]. In particular, deep cycle batteries are frequently emphasised in the literature, with efficiency levels ranging from 70% to 90% [82]. Subsequent sections of this review provide more detailed discussions regarding some of the commonly employed batteries as found in the literature.

4.1.3.1. Lithium-ion (Li-ion). Li-ion batteries offer several advantages when applied in MG development, including high energy density, efficient trade-offs between specific energy and specific power ratings, safe operating temperatures, and relatively long expected lifespans [83,84]. Nonetheless, it is important to note that Li-ion batteries have a notable limitation. Specifically, their lifespan is significantly affected by the depth-of-discharge, which necessitates the implementation of advanced and often more expensive operational strategies [85].

4.1.3.2. Lead-acid (LA). The lead-acid battery stands as the most commonly used battery technology in remote, off-grid MGs [86]. It provides certain advantages such as deep cycle discharge capacity and low self-discharge rates, all at a comparatively affordable cost due to its mature and well-established technology base. However, it is important to note that lead-acid batteries have some limitations. They possess low specific energy, relatively limited charge and discharge power capacities, reduced performance in low temperatures, and a restricted cycle life, with frequent deep cycling significantly diminishing their longevity [87].

4.1.3.3. Vanadium redox-flow. Vanadium redox-flow batteries offer several key advantages, including high energy efficiency, extended cycle life, rapid response times, and the ability to independently adjust power ratings and energy capacity. However, it is worth noting that they are currently associated with higher capital and O&M costs. A significant portion of these costs is attributed to the use of capital-intensive ion-exchange membranes, which typically contribute to approximately 40% of the total battery cost [88]. Additionally, these batteries have limitations in terms of their volumetric energy storage capacity due to the low solubility of active species in the electrolyte. Despite these challenges, the literature review highlights the valuable role of vanadium redox-flow batteries in improving power quality in accordance with their high charge/discharge power capacities [89].

4.1.3.4. Sodium-sulfur (NaS). The sodium-sulfur battery technology stands out as a mature system with well-established experience and moderate costs per capacity when compared to other battery technologies. It boasts several advantages, including minimal self-discharge and an exceptionally rapid response time, characterised by high energy density, energy capacity, and power density. These attributes make it particularly suitable for addressing changes in demand within a MG's steady-state conditions. Furthermore, sodium-sulfur batteries contribute to environmental sustainability due to their high recycling rate, driven by the use of less toxic materials [90].

However, it is important to note a significant drawback of sodium-sulfur batteries. They require a heat source to maintain the temperature of the liquid electrode, with an operating temperature typically ranging from 574 K to 624 K. This requirement renders them impractical for residential use. Moreover, the necessity of a heat source impacts the battery's efficiency, leading to reduced overall efficiency and additional costs incurred for the implementation of heat exchange systems [91].

4.1.3.5. Nickel-metal hydride (NiMH). The nickel-metal hydride (NiMH) battery possesses several advantageous qualities, including a low memory effect, strong environmental performance, profitability for recycling, long service life, and relatively affordable cost [92]. However, it faces certain challenges, such as high self-discharge rates, typically ranging from 25% to 35% per month, a limited cycle life with performance deterioration after fewer than 300 cycles when repeatedly deep discharged, low charging/discharging power capacities, and elevated maintenance costs [93].

As highlighted in the review of various batteries used in MGs, distinct battery storage technologies exhibit varying specifications, notably encompassing energy density, specific power, specific energy, charge/discharge power capacity, self-discharge rates, and maximum allowable depth-of-discharge. This necessitates the execution of comprehensive, multi-case-study-oriented comparative analyses of diverse battery technologies. Such studies would help guide decision-making processes related to optimal MG capacity planning and unit sizing during the long-term strategic planning phases.

It is also crucial to recognise that the disparities in specifications among different battery technologies significantly influence the outcomes of energy balance analyses performed during the year-long operational scheduling stage. These disparities subsequently lead to adjustments in optimal equipment sizes and the total discounted life-cycle costs of MGs [94]. Furthermore, comprehensive battery selection studies serve as effective platforms for enhancing the profitability of renewable energy project developments, reducing energy curtailments, and minimising lost loads.

4.1.4. Lack of operation and maintenance resources

The relatively new and less mature state of renewable energy technology has given rise to a significant knowledge and expertise gap in O&M practices. This knowledge deficit results in operational inefficiencies and suboptimal maintenance practices, leading to lower-than-expected system efficiencies. To maximise efficiency, it is imperative that renewable energy technologies are operated optimally, adhering to a well-defined maintenance schedule.

Another critical consideration in the planning stages of renewable energy projects is the availability of suitable equipment, components, and spare parts within local markets. The importation of equipment, when local alternatives are available, can significantly inflate initial project costs, consequently elevating the overall estimated project expenditure [95]. Therefore, a comprehensive assessment of the local market's capacity to provide necessary equipment and components should be conducted during the techno-economic feasibility phase of project planning to ensure cost-effectiveness and long-term sustainability.

4.2. Economic barriers

The literature review also uncovers that the primary factors contributing to the economic and financial barriers encompass high initial capital requirements, the absence of appropriate financial institutions, limited investor participation, and government subsidies in developing, oil-exporting nations [96]. These factors have impeded the worldwide expansion of renewable energy. The subsequent sections provide a more detailed examination of the identified economic barriers.

4.2.1. Competition with fossil fuels

According to the International Energy Outlook report by the U.S. Energy Information Administration [97], fossil fuels, primarily coal, natural gas, and oil, are projected to contribute 78% of the global energy supply (aggregated across all sectors) by 2040. For illustrative purposes, Fig. 7 depicts global electricity production by source up to 2022 [98]. It is noteworthy that coal continues to play a major role in power generation due to its abundance in many countries, making it a relatively inexpensive and accessible option compared to renewable energy technologies. Additionally, natural gas-fired power plants and natural gas combined-cycle power plants constitute a significant portion of the power generation mix in developing nations that rely on fossil fuel exports [99].

4.2.2. Subsidies of energy generation

In developing nations heavily reliant on fossil fuel exports, the energy landscape remains characterised by significant government subsidies directed toward fossil fuel-fired power generation. This substantial financial support has created economic disincentives for the widespread integration of RESs within the corresponding power generation sectors. For instance, one pertinent example is Iran, where natural gas constitutes a dominant 70% share of the power generation mix. In 2020 alone, these natural gas resources received substantial subsidies amounting to $35 billion [100]. This persisting preference for fossil fuel subsidies over investments in RESs contributes to economic barriers to renewable energy adoption in such regions.

4.2.3. Renewable energy investment with limited financing institutions

In the absence of dedicated financial instruments and organisations tailored for renewable energy projects, financing these projects often resorts to either corporate finance or project finance structures. Corporate finance hinges on the balance sheet of an entity, such as a utility company, while project finance operates through a distinct legal entity kept off the balance sheet. Notably, a significant portion of renewable energy market openings, spanning various scales of development, is attributable to private developers. Paradoxically, even high-risk renewable energy ventures may necessitate public funding, yet it remains private entities that leverage public financial mechanisms to advance renewable energy into less well-explored territories [101].

Furthermore, attaining financing at rates competitive with those

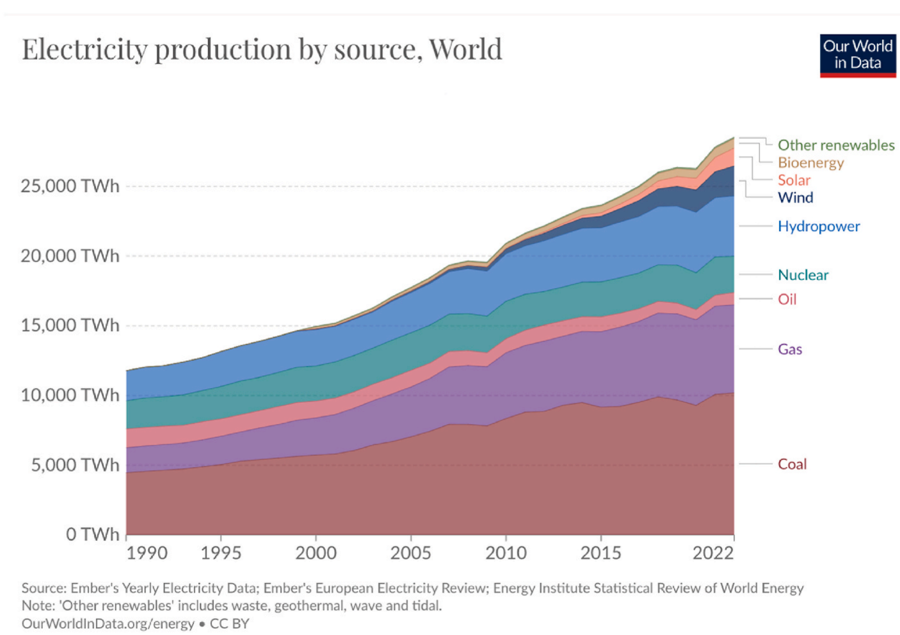


Fig. 7. Global electricity production by source until 2022 [98].

available to fossil fuel energy projects poses a considerable hurdle for renewable energy developers, particularly in the developing world. To address this challenge, the literature advocates for a hybrid debt-equity finance structure. In this context, debt represents the portion of investment sourced from external lenders, supported by the project's financial flows or the corporate entity's credit. Equity, on the other hand, embodies the residual value that would be realised upon liquidation of all project assets based on future cash inflows generated by the project. Establishing the optimal debt-equity ratio in the project's financial structure necessitates comprehensive risk-informed capital budgeting analyses [102].

4.2.4. Cost of capital

Renewable energy initiatives often entail substantial initial investment costs, further compounded by inefficiencies in technology deployment. These inefficiencies translate into extended net payback periods, which denote the time required to recover the initial investment costs. These prolonged payback periods can deter potential investors [103]. Within the energy sector, both the energy-as-a-service (EaaS) and community-financed business models grapple with this challenge, as they necessitate significant upfront capital expenditures. The issue is more pronounced in regions where stringent lending standards prevail, making access to loans without substantial creditworthiness a significant obstacle [104].

4.3. Social barriers

Despite widespread public support for renewable energy, certain regions have encountered resistance and opposition to transitioning from conventional energy sources to renewables, particularly in the context of infrastructure siting. This resistance often stems from a dearth of reliable information. The review underscores that while substantial research has delved into public attitudes toward sustainable energy infrastructure, a comprehensive understanding of the intricacies of social acceptance remains elusive. This is primarily attributed to the limited consideration of all the determinants of social acceptance concurrently in existing studies [105].

4.3.1. Symbolic aspects of facility siting

A review of the literature highlights the necessity for a more systematic exploration of the symbolic aspects within renewable energy infrastructure siting disputes, as empirical studies focusing on such dimensions are limited. Recent research has also adopted a discursive approach to gain deeper insights into public resistance regarding the placement of wind turbines, solar PV panels, and micro-hydro generation systems. These studies have illuminated the role of rhetorical and communicative elements at the social-psychological level, demonstrating their potential to positively influence the decisions of individuals and local communities engaged in disputes related to renewable energy siting [105,106].

4.3.2. Not-in-my-backyard phenomenon

The "not-in-my-backyard" phenomenon, often referred to as NIMBY, characterises instances where individuals express opposition to the local implementation of a technology or service, despite their overall abstract support for the concept. Noteworthy factors contributing to NIMBY behaviour include concerns related to landscape alteration, environmental harm, noise disturbances, perceptions of government concessions of public lands to private solar and wind farm developers, and the potential devaluation of local property values [107–109].

4.3.3. Land use

The inherent characteristics of wind turbines and solar PV panels, specifically their land requirements per unit of power produced, often lead to conflicts over land use and project siting, resulting in opposition from farming communities to the development of renewable energy projects near their lands [96]. Consequently, a growing body of research has been dedicated to mitigating the land use impact of renewables. Strategies such as integrating renewable power generation with other land uses, particularly agriculture, and the installation of solar panels on rooftops have emerged as effective interventions to minimise land use conflicts. Additionally, involving communities directly in renewable energy planning and land use zoning has been recognised as a valuable policy approach to help alleviate such concerns [110,111].

4.3.4. Lack of skilled labour

The literature review also highlights the shortage of skilled professionals with expertise in designing, constructing, operating, and maintaining renewable energy and storage technologies, which is crucial for a smooth transition to a low-carbon economy [112]. Bridging this skills gap is not only essential for improving energy access but also plays a pivotal role in realising the goal of achieving 100% renewable energy [113]. To drive the renewable energy transformation in the post-COVID19 era, there is a dire need for increased investment and innovation in higher education, as well as long-term commitments to staffing.

4.4. Legal and regulatory barriers

Several legal and regulatory barriers to the adoption of sustainable energy systems have been identified, including the absence of legal frameworks and standards for independent power generators, restricted access to transmission and distribution lines, mandatory liability insurance requirements, and a lack of equipment standards [114,115].

4.4.1. Lack of legal frameworks and standards for independent power generators

In numerous developing nations, electricity companies still maintain a monopolistic control over the entire energy supply chain, encompassing generation, transmission, and distribution. Under these circumstances, characterised by a deficiency in standardised legal frameworks, independent electricity generators encounter barriers to market entry and investment in sustainable energy systems with EaaS business models. These conditions also give rise to ad-hoc, non-systematic power purchase agreements, significantly complicating the planning and management of renewable energy development [115,116].

4.4.2. Limited transmission and distribution line access

In situations where conventional power utilities maintain a monopoly over transmission and distribution lines, they may not provide fair access to these lines for emerging renewable energy generation companies. Ensuring equitable access to the power lines is particularly critical for renewable energy generation companies, such as wind and solar farms and large-scale biopower plants, which are often located at a considerable distance from consumption nodes. Consequently, the establishment of clear and consistent regulations becomes imperative to effectively prevent right-of-way disputes [115,117].

4.4.3. Liability insurance requirements

Small-scale renewable energy systems, especially solar PV-based household and community systems that contribute excess energy to the grid under net metering tariffs, may necessitate liability insurance. This requirement arises from the potential risk associated with these small generators continuing to supply electricity to the broader utility grid when the main power lines are disconnected for maintenance, which could pose a danger to repair crews. However, it is worth noting that modern protective devices can mitigate this concern, known as the "islanding" issue [115,118].

4.4.4. Lack of equipment standards

Standardisation within the renewable energy supply chain is crucial to ensure that equipment and spare parts adhere to technical regulations. The development of effective standards involves thorough verification processes that benchmark against specific criteria. It also encompasses conformity assessment procedures conducted through independent third-party certifications or other verification methods [119].

5. Drivers of sustainable energy systems

The literature review has also highlighted that the drivers of renewable energy development can be broadly categorised into four groups, either individually or in combination, namely: (i) climate change mitigation, (ii) energy security, (iii) energy access, and (iv) socio-economic growth. Further elaboration on these drivers is provided in the subsequent sections.

5.1. Climate change mitigation

Efforts to address climate change by limiting global temperature rise to well below 2°C, or even striving for the more ambitious target of 1.5°C, serve as a significant driving force behind the widespread adoption of renewable energy [120]. Considering that energy consumption is responsible for approximately two-thirds of total GHG emissions, with the power generation sector being a major contributor, the imperative of decarbonising the energy sector, including power generation, through renewable sources is of paramount importance. Currently, renewables constitute approximately 29% of the global power generation mix, and this figure is projected to surge to nearly 60% by 2030 [121].

5.2. Energy security

Energy security is of particular relevance when it comes to providing clean and affordable energy to remote and less economically developed communities, especially considering that many remote areas currently rely on diesel as their primary energy source. Apart from the adverse environmental impacts associated with diesel usage, its prevalence in remote regions raises significant energy security concerns. To address this issue, the literature highlights the efficacy of local renewable energy systems employing diversified technologies in enhancing energy security for remote, off-grid applications, while simultaneously reducing energy-related costs [122]. This transition to renewable energy not only mitigates environmental harm but also bolsters energy security in such communities.

5.3. Energy access

While global access to electricity has steadily increased in recent decades, it is worth noting that 940 million people, which accounts for approximately 13% of the world's population, still lack access to electricity. Historically, this lack of access was primarily attributed to the cost-inefficiency of extending power lines from the electricity grid to these underserved areas. However, the advent of advanced smart MGs has ushered in a new era marked by significant advancements in the cost-effectiveness and efficiency of renewable energy and energy storage technologies. This progress has provided a compelling platform to expedite the electrification of remote and low-income communities [123].

Furthermore, the integration of advanced water purification, filtration, treatment systems, and even water desalination technologies within standalone MGs customised for communities lacking access to safe drinking water has offered effective solutions to address clean water challenges in various instances [124]. This integrated approach not only provides electricity but also addresses critical water needs, thus significantly improving the overall quality of life in these underserved areas.

5.4. Socio-economic growth

Prior research has also established a direct correlation between the human development index (HDI) and per capita income with per capita energy usage [96]. This means that measuring a community's electricity consumption serves as a significant social and economic indicator, with far-reaching implications for various aspects of well-being, including health, education, and overall quality of life [125–127].

In this context, off-grid, integrated, and smart energy systems that locally generate electricity through RESs have emerged as a valuable tool for promoting sustainable rural development. These systems offer the potential for multifaceted socio-economic benefits, including the creation of net job opportunities and enhanced social inclusiveness [128]. By providing clean and reliable energy, these systems not only contribute to improved living conditions but also empower communities to pursue an effective path of sustainable development.

6. Optimal system configuration and equipment capacity planning problem

Given the substantial emphasis within the reviewed literature on optimising system configurations and determining the optimal component sizes for RSESs, this section provides a comprehensive examination of the following aspects:

- Primary objectives: Discusses the main objectives addressed in the literature.
- Key constraints: Explores the primary constraints imposed on these optimisation efforts.
- Optimisation approaches: Presents the prevailing approaches employed for optimisation.
- Integrated technologies: Highlights the key technologies integrated into these systems.
- Business models: Synthesises the literature concerning the underlying business models.

6.1. Prime objectives

A diverse array of decision criteria has been examined in the pertinent literature on energy planning optimisation, categorised broadly in Fig. 8 based on the level of analysis. It also provides a percentage breakdown of the optimisation objectives explored in the literature under review.

While practically all reviewed studies inherently include system cost as a criterion for decision-making, a recent and growing body of literature has illuminated the potential advantages of moving beyond pure cost optimisation. It is increasingly recognised that integrating non-monetary decision criteria, in conjunction with total discounted system cost, into the foundational long-term strategic energy planning optimisation problems can offer a robust framework for yielding truly optimal energy planning solutions. This approach aims to provide a more accurate approximation of real-world complexities.

As depicted in Fig. 8, this evolving literature explores a range of new non-financial decision criteria, thereby paving the way for multi-objective long-term energy planning decision-making models. Among the objectives simultaneously optimised alongside cost minimisation are environmental impact reduction, enhancement of power supply reliability, and social acceptability considerations. In this context, the most common multi-criteria energy planning optimisation models enable the examination of the complete Pareto-optimal trade-offs among cost minimisation, environmental sustainability, and power supply reliability.

While substantial efforts have been dedicated to incorporating a diverse array of optimisation objectives to enhance the precision of long-term energy planning solutions, the systematic literature review also

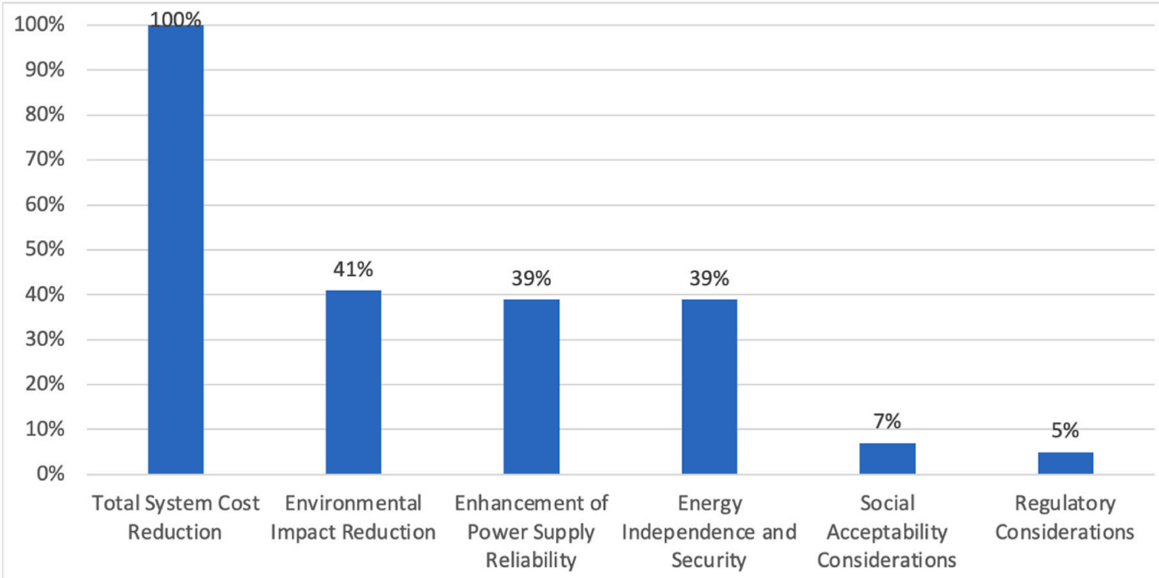


Fig. 8. Percentage distribution of the main decision criteria addressed in the energy planning optimisation literature.

underscores that relatively less attention has been afforded to investigating the potentially substantial role of social and regulatory criteria in achieving more nuanced representations of design preferences. This research gap invites further exploration into the integration of social and regulatory objectives within the multi-objective and environmental categorisations, fostering a more holistic and comprehensive approach to long-term energy planning optimisation.

6.2. Key constraints

Constraints in energy planning optimisation can broadly be categorised into two main groups, namely: those associated with the operation and dispatch of the system, and those related to the long-term planning of the system. Specifically, constraints related to generation capacities, technical limitations of energy storage devices, supply-demand balance, voltage drop limitations, network stability, and power exchanges with the wider utility network are notable considerations during the optimal energy scheduling phases. On the other hand, constraints that unfold over longer timescales, such as reliability, resilience, adequacy, security, and self-sufficiency, come into play during the planning phases.

Recent advancements in meta-heuristic-based optimisation algorithms [129] have made them particularly adept at handling discontinuous or concave Pareto fronts, as they are less sensitive to the shape of the underlying Pareto front. Population-based meta-heuristics, which are more commonly employed in energy planning optimisation literature, offer the ability to generate multiple elements of the underlying Pareto-optimal set of solutions when dealing with multiple conflicting objectives in a single run.

Nevertheless, exact mathematical optimisation-based solution algorithms continue to hold a significant role in multi-criteria optimisation approaches designed for long-term strategic energy planning. Of notable importance, the ε-constraint method [130] stands as the predominant exact mathematical optimisation-based approach in the literature for incorporating more than one objective function (which is most commonly a cost function) within the overarching multi-criteria optimisation problem. The fundamental concept behind energy planning optimisation approaches rooted in the ε-constraint method involves transforming non-monetary objectives into a set of constraints and subsequently solving the resulting single-objective cost minimisation/profit maximisation model instance multiple times to estimate the associated Pareto-front of non-dominated solutions. More specifically, non-monetary objective functions are converted into constraints by constraining them not to exceed certain predefined values, derived from different maximum or minimum allowable values. The associated single-objective model is then solved for various combinations of these predefined values to generate Pareto-optimal solutions aligned with the original multi-criteria problem.

In addition to the constraints mentioned above, energy planning optimisation also grapples with regulatory and social constraints. Regulatory constraints encompass legal frameworks, standards, and policy guidelines that dictate the permissible practices and configurations of energy systems. Social constraints pertain to public opinion, community acceptance, and local resistance, which can influence the siting and operation of renewable energy infrastructure. Furthermore, technical constraints related to equipment capabilities and reliability constraints linked to system dependability are integral components of energy planning optimisation, although they are not explicitly mentioned in the preceding sections.

These various constraints collectively contribute to the complexity of the energy planning optimisation problem, necessitating a holistic approach that considers technical, financial, environmental, regulatory, and social factors to yield sustainable and optimal solutions.

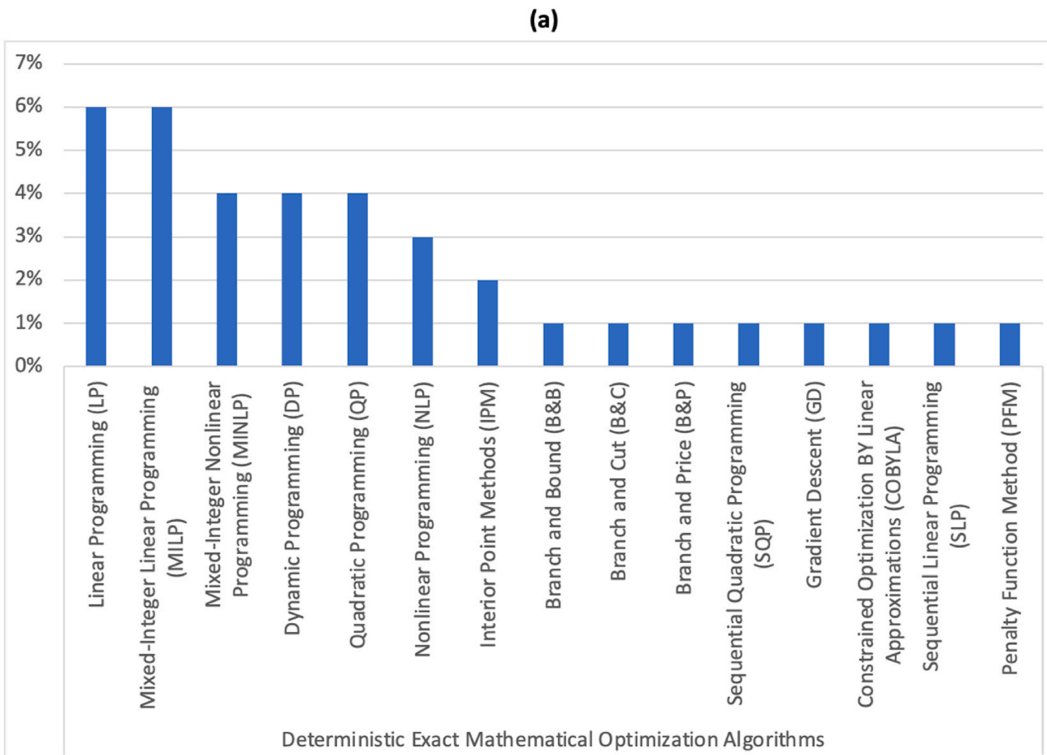
6.3. Mainstream optimisation approaches

Optimally determining the configuration of components integrated into MGs, such as solar PV panels, wind turbines, micro-hydro power plants, battery storage systems, and hydrogen-based energy storage systems, is a complex task. This complexity arises from the need to assess the operational performance of various combinatorial configurations efficiently. To address this challenge and ensure computational tractability, intelligent optimisation-based methodologies are employed [131].

It is important to highlight that MG design and operation are intricately linked problems. Operational strategies have a direct impact on the required equipment capacity, and conversely, system capacity constraints can influence optimal operational decisions. Furthermore, uncertainties in forecasted data play a pivotal role in shaping system operations. These uncertainties propagate upwards, affecting the optimal sizing problem [94]. Beyond aleatory sources of uncertainty, the MG capacity planning optimisation problem is also associated with epistemic uncertainties, arising from the lack of knowledge regarding future scenarios that cannot be modelled probabilistically [132].

In this context, as depicted in Fig. 9, a spectrum of methodologies has been explored in the literature to arrive at optimal MG designs while considering technical and economic constraints at both operational and planning levels. The subsequent sections categorise the broader MG sizing approaches and critically evaluate the most robust methods for optimising MG design and investment planning, as presented in the reviewed literature.

As previously mentioned, practically all the MG sizing approaches involve the evaluation of various design configurations by assessing the system's operational performance at discrete time intervals over a



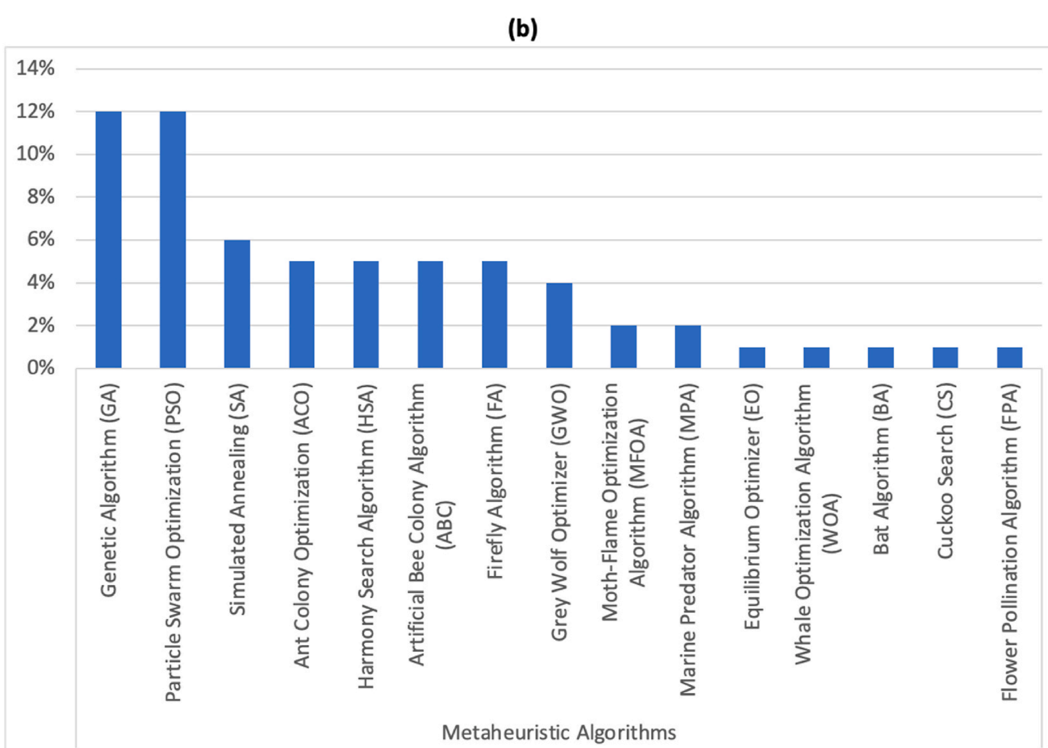


Fig. 9. Percentage contribution of (a) exact mathematical and (b) meta-heuristics algorithms to solving the energy planning optimisation problem.

specified duration. This inherently introduces computational complexity into the problem. The conventional method for MG sizing leverages precise mathematical programming techniques, including linear programming, mixed-integer linear programming (MILP), mixed-integer nonlinear programming (MINLP), and dynamic programming. Although these techniques offer relative computational efficiency, their precision is compromised due to the need for multiple decompositions and mean-field approximations when applied to the non-deterministic polynomial time-hard (NP-hard) MG sizing problem. This problem often encompasses integrated nonlinear and non-convex objective functions, alongside planning and dispatch-level constraints [133].

An expanding body of literature has also developed multi-objective models to address the strategic, long-term MG capacity planning optimisation when multiple criteria are involved. This segment of the literature focuses on optimising objectives related to reliability, GHG emissions, curtailed energy, self-sufficiency, and resilience concurrently with the total discounted system cost. Unlike the traditional single-objective approach that treats these factors as constraints and aims primarily at cost minimisation, multi-objective energy planning optimisation aims to make informed decisions while acknowledging trade-offs among various competing objectives.

As mentioned earlier, the predominant approach in the literature for multi-criteria MG planning optimisation is the ε-constraint method. The ε-constraint method is essentially an algorithmic transformation approach, with a primary advantage being its ability to control the representation density of each objective. This is achieved by assigning a set of equidistant grid points to other objectives and treating them as constraints. However, the drawback of this method is that it involves breaking down a multi-objective problem into several single-objective problems and solving them for various input settings, making it computationally expensive, especially for large-scale problems. Consequently, the ε-constraint method falls short in generating a set of non-dominated solutions in a single run [134,135].

To address the computational complexity inherent in NP-hard MG sizing applications, recent literature has increasingly focused on meta-heuristic-based solution approaches for MG capacity planning optimisation. Meta-heuristics offer the advantage of adaptability to full models, but they are subject to the so-called "no free lunch" theorem. This theorem posits that there is no universally superior meta-heuristic algorithm that outperforms all others across all scenarios.

This necessitates comprehensive, multi-test-case-oriented efficiency testing of meta-heuristics, especially given the rapid advancements in this highly active field [94,136]. In light of the approximate nature of meta-heuristics, they employ iterative, nature-inspired master processes to guide and modify the operation of the underlying heuristics (low- or high-level procedures) to effectively produce high-quality solutions [137].

In single-objective, least-cost-based MG sizing applications, this involves assessing the fitness of each search agent, particle, or individual in the meta-heuristics at each iteration by evaluating the associated operational performance of the candidate solution set. The solution set comprises the size of components as decision variables and the corresponding total discounted cost of the system. The iterative process of searching for the cost-minimal solution then continues until the stopping criterion is met, typically a maximum number of iterations. Furthermore, multi-objective variants of meta-heuristics have proven to be particularly effective in solving multi-criteria MG design optimisation problems compared to analytical methods.

A review of the relevant literature also reveals that the multi-objective evolutionary algorithms utilised in MG sizing applications can be broadly classified into two main categories: Pareto-based and non-Pareto-based algorithms. Pareto-based algorithms are more prevalent in the literature due to their ability to provide valuable insights into the best-compromise solutions.

Furthermore, in terms of the subordinate heuristics utilised, meta-heuristics can be generally categorised into the following two classes:

(i) Trajectory meta-heuristics: Trajectory meta-heuristics typically employ a single agent at a time to trace a path over the course of iterations. Commonly used meta-heuristics in this category include simulated annealing algorithm (SAA), tabu search (TS), greedy random adaptive search procedures (GRASP), evolutionary strategy (ES), and iterated local search (ILS) [94].
(ii) Population-based meta-heuristics: Population-based meta-heuristics involve multiple search agents that interact with each other and explore multiple paths as iterations progress. The most commonly used meta-heuristics in this category include the genetic algorithm (GA) and particle swarm optimisation (PSO) [94].

Moreover, the MG capacity planning literature has witnessed the proposal and application of various meta-heuristic hybridisations. The fundamental concept behind hybridising different meta-heuristics is to leverage the strengths of one meta-heuristic to compensate for the weaknesses of another, creating an effective platform for cross-pollinating different meta-heuristic optimisation approaches. Additionally, these efforts in meta-heuristic hybridisation can be broadly categorised into sequential and parallel approaches, with parallel algorithms offering the advantage of reduced execution times [138].

Furthermore, the category of non-Pareto-based multi-objective meta-heuristics, alternatively referred to as single-objective-based multi-objective meta-heuristics, frequently employs the weighted sum method to amalgamate all multi-objective functions into a single scalar, composite objective function. This group of algorithms possesses the advantage of yielding a single unique solution suitable for real-world implementation. However, it does not facilitate decision-making by identifying a preferred solution among the Pareto-optimal solutions; instead, it offers a set of alternatives. This approach is often considered subjective because it entails the direct assignment of weights by decision-makers [139].

In contrast, Pareto-based multi-objective optimisation algorithms provide the non-dominated set encompassing the entire feasible decision space. To illustrate, when one solution dominates another, it implies that it is strictly superior to the other solution in at least one objective while being no worse in all other objectives. Within a set of multi-criteria solutions, the non-dominated solution set comprises all solutions that are not dominated by any other solution within the set. The collection of non-dominated solutions within the feasible decision space is termed the Pareto-optimal set. Additionally, the boundary formed by the points derived from the Pareto-optimal solutions is referred to as the Pareto-optimal front [133,140].

It is worth noting that two fundamental components shared by all meta-heuristics involve the generation of an initial random population of solutions and their subsequent evolution towards global optimality. These components are known as intensification and diversification, alternatively referred to as exploitation and exploration, respectively. The exploitation phase is responsible for facilitating effective long-range movements across the global search space, whereas the exploration phase aims to conduct efficient local searches near the global optima. Striking the right balance between these two components is crucial to ensure the achievement of global optimality by meta-heuristics [138].

6.3.1. Major trends in meta-heuristic-based MG sizing approaches

The literature review highlights several prominent trends in meta-heuristic-based MG sizing. Notably, the PSO [141] and the GA [142], along with their multi-objective variants, emerge as dominant meta-heuristics in the literature. For example, Nikmehr and Ravadanegh [143] introduced a PSO-based solution algorithm for optimising the sizing of grid-connected MGs, which takes into account optimal power exchange decisions between the MG and the primary utility grid. The PSO has also been applied by Samy and Barakat [144] to optimise MG sizing that incorporates solar PV and biomass generation resources, with performance comparisons against the invasive weed optimisation (IWO) method. These optimisations consider the total net present cost (TNPC) as the primary objective, while adhering to constraints on the maximum allowable total excess energy fraction and the loss of power supply probability (LPSP).

As another example, a PSO-based MG sizing solution algorithm has been proposed for both grid-connected and islanded solar PV/wind MGs in Ref. [145]. This algorithm has demonstrated the capability to produce statistically robust and valid results for addressing the MG capacity planning problem. In another study, Karuppasamypandiyan et al. [146] utilised the non-dominated sorting genetic algorithm-II (NSGA-II) to optimise both cost and GHG emissions in a MG that integrates wind turbines, solar PV panels, fuel cells, and a diesel generator. Similarly, Mosbah et al. [147] presented a solution approach for simultaneously optimising cost and voltage stability in grid-connected MGs, employing the NSGA-II algorithm. Furthermore, in a comprehensive study that encompasses multiple cases, Hlal et al. [80] demonstrated that the NSGA-II algorithm generates statistically robust solutions for MG planning problems involving multiple conflicting objectives, outperforming the multi-objective PSO in this application, albeit with increased computational complexity.

More recently, the moth-flame optimisation algorithm (MFOA) [148], inspired by the navigation behaviour of moths at night (referred to as transverse orientation), has emerged as an efficient algorithm for MG sizing applications. In several studies, the MFOA has demonstrated its effectiveness in optimising MG sizing solutions. For instance, Mohseni et al. [149] showed that the MG sizing solutions optimised using the MFOA outperforms those obtained through various other algorithms, including the GA, PSO, hybrid GA-PSO, harmony search algorithm (HAS), SAA, artificial bee colony algorithm (ABCA), ant colony optimiser (ACO), and ant lion optimiser (ALO).

The literature review also highlights the increasing attention given to hybrid meta-heuristic approaches in recent years [150,151]. For instance, Suresh and Ganesh [152] demonstrated the enhanced efficiency of a hybrid algorithm combining the MFOA with the bat search algorithm (BSA) for capacity planning in MGs that incorporate solar PV, wind turbines, fuel cells, and battery storage resources. Their research has not only introduced this hybrid approach but it has also introduced the consideration of both active and reactive power aspects during the MG design phase – a crucial factor for enhancing power supply quality.

A growing body of literature has also delved into the optimal integration of electric vehicles (EVs) within MGs, with significant implications for system dispatch strategies [153]. For instance, Rasouli et al. [154] introduced a MILP approach aimed at optimising the integration of EVs into systems primarily powered by solar PV and micro-turbine resources. Their study also addressed the quantification of uncertainties associated with forecasts of EV-charging loads, electricity market prices, residential loads, and the power outputs from solar PV and micro-turbine technologies.

A similar MILP modelling approach for EV integration has been employed in Ref. [155] in the context of systems incorporating wind resources, boilers, combined heat and power units, storage technologies, and responsive loads. Their study has also involved the characterisation of uncertainties related to wind speed and load demand.

In contrast, Yi et al. [156] introduced a fundamentally different modelling framework based on the SAA algorithm. Their approach focused on the integration of EV-charging loads within systems that include solar PV panels and wind turbines. Additionally, they considered the optimisation of power exchange schedules with the broader utility grid.

6.3.2. *Growing potential of meta-heuristics*

As demonstrated in the overview of MG planning literature, meta-heuristic algorithms have gained increasing prominence in the optimal planning and design of RSESs. Fig. 10 provides a summary of the percentage contribution from various sources of inspiration for these meta-heuristics, which represent the underlying principles or strategies derived from natural or artificial systems that guide the design and behaviour of the algorithms [157].

Furthermore, the review has highlighted the effectiveness of model-order reduction in addressing the inherent computational complexity associated with meta-heuristics. For example, Cagnano et al. [158] employed a reduced model for voltage control profiles while optimising component sizes within the network. Similarly, Chaspierre et al. [159] introduced a reduced-order model to simplify the distribution network during the planning phase. Ramli et al. [160] considered lower-than-standard resolution for wind speed, solar irradiance, ambient temperature, and load data while optimising MGs that integrated solar PV, wind turbines, and diesel generator technologies. In a similar vein, Augustine et al. [161] utilised representative days to mitigate the computational demands when optimising the total planning

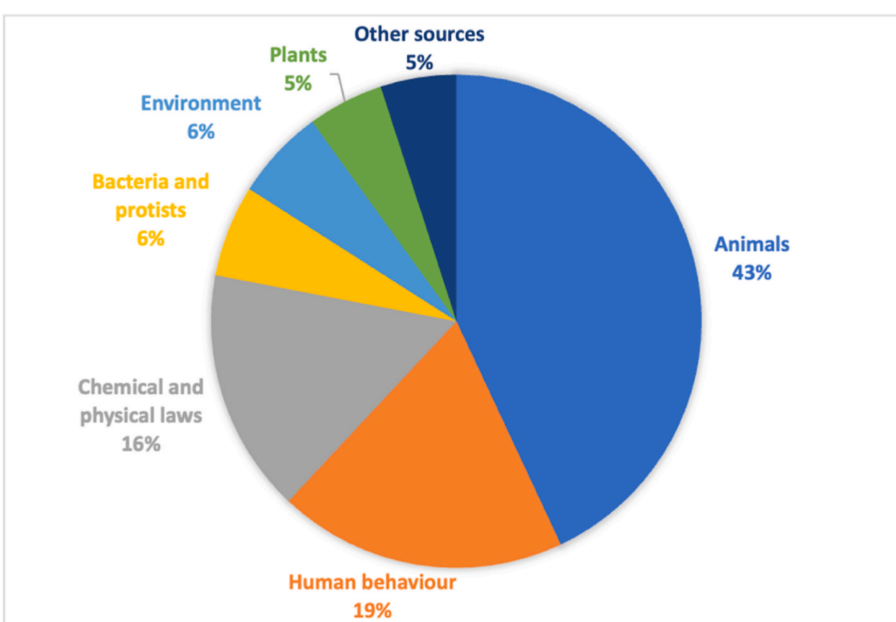


Fig. 10. Distribution of inspiration sources of meta-heuristics in the literature (adapted from Ref. [162]).

cost of an MG.

Furthermore, a growing body of literature provides compelling evidence supporting the argument that newly advanced, state-of-the-art meta-heuristics hold the potential to improve the optimality and quality of energy optimisation solutions, including those related to MG sizing, when compared to well-established algorithms. For instance, Ramadan et al. [163] demonstrated that the wild horse optimiser (WHO), a biology-inspired algorithm inspired by the social behaviours of wild horses such as domination, grazing, leading, chasing, and mating, outperforms the evolutionary algorithm (EA) and gradient-based optimiser (GBO) in modelling the nonlinearity of solar PV panels. In another study, Ali et al. [164] showcased the superior performance of the artificial gorilla troops optimiser (AGTO) over established meta-heuristics in modelling the frequency response of energy systems incorporating solar PV panels, wind turbines, diesel generators, and battery storage devices. Their research has further established the statistical robustness and validity of these findings through simulations conducted across a range of battery storage technologies.

Moreover, Alharthi et al. [165] highlighted the superior efficiency of a multi-objective variant of the marine predator algorithm (MPA) compared to well-established multi-objective meta-heuristics in the context of optimal dispatching applications for energy systems. This approach simultaneously considers multiple conflicting objectives, including energy losses, total cost, carbon dioxide emissions, and fuel costs. Similarly, Wadood et al. [166] demonstrated the effectiveness of the MPA when compared to conventional meta-heuristics in minimising the total operational time of relays – a critical factor in reducing interference and failure rates in MG systems. In another instance, Ahmed et al. [167] showcased the improved effectiveness of the equilibrium optimiser (EO) in addressing multi-objective MG energy management problems that encompass cost minimisation, voltage profile maximisation, and system stability enhancement as simultaneous goals.

6.4. Primary technologies

In general, the selection of renewable energy generation technologies for integration into RSESs is context-specific and hinges upon the renewable energy potentials unique to the site of interest. These chosen generation technologies constitute the candidate pool for energy planning and unit sizing problems, and their appropriateness is determined through meticulous assessments of renewable energy resources. Conversely, the choice of storage technologies involves more discerning factors, such as the presence of a utility grid, the community's aspirations to harness value-enhancing services such as grid arbitrage and ancillary services provision, the degree of seasonality in both energy demand and generation, the consideration of feed-in-tariffs, the existence of dispatchable renewable generation components (notably bioenergy sources), the evaluation of probabilities regarding harmonic stability issues, constraints associated with system reliability, resilience, and self-sufficiency, the availability of fast demand response capacities, and other context-specific determinants. These considerations are distilled during the selection process.

However, despite the multifaceted factors influencing the selection of generation and storage technologies for integration into RSESs, with a particular focus on MGs, several recurrent themes emerge within the literature, particularly concerning technological scope. To illustrate these trends, Figs. 11 and 12 respectively provide summaries of the distribution of generation and storage technologies within the pertinent reviewed studies.

The global shift towards RESs has been substantially bolstered by significant reductions in the costs associated with wind and solar renewable energy technologies over the past decade. These cost reductions have been complemented by unprecedented technological advancements that have transpired over the last two decades. Notably, a considerable percentage of the reviewed studies, comprising 35% and 25% of the total, endorse the integration of solar and wind technologies into RSESs. Conversely, none of the studies identified advocates for the inclusion of nuclear energy within the energy portfolio mix. However, fossil fuel-based generation continues to hold a modest presence in both bulk and micro power systems in the form of thermal generators and diesel generators, respectively.

More specifically, coal and natural gas-fired power plants constitute the primary fossil fuel-based generation technologies in bulk power systems. In contrast, diesel-engine generators are the prevalent choice for providing backup power in community-scale hybrid renewable energy systems, particularly in off-grid applications.

In the realm of storage technologies integrated into RSESs, the literature reveals a dynamic landscape driven by several compelling factors. Much of the focus has centred on addressing the temporal aspects of renewable energy generation, grid interactions, and the

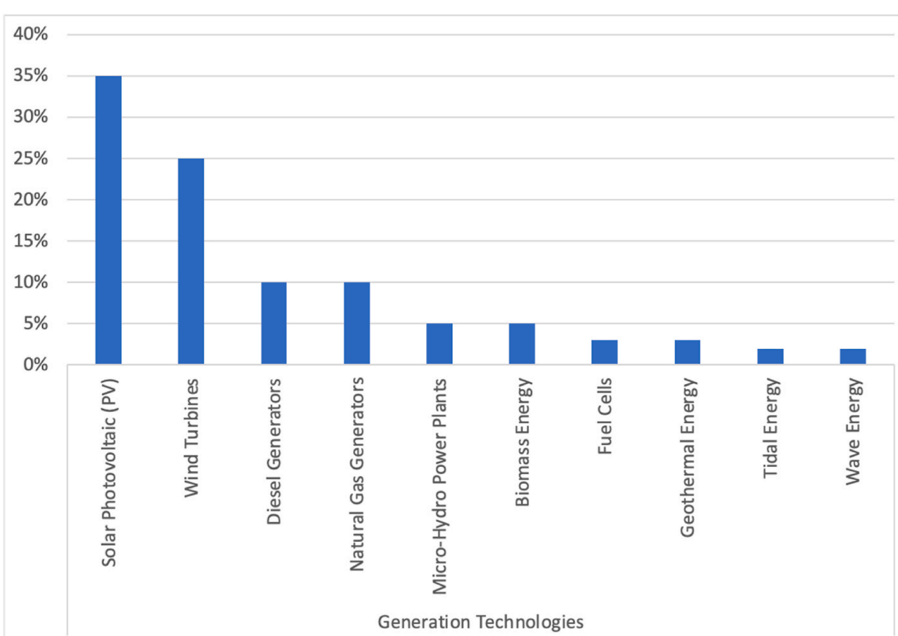


Fig. 11. Summary of the distribution of generation technologies in the reviewed literature.

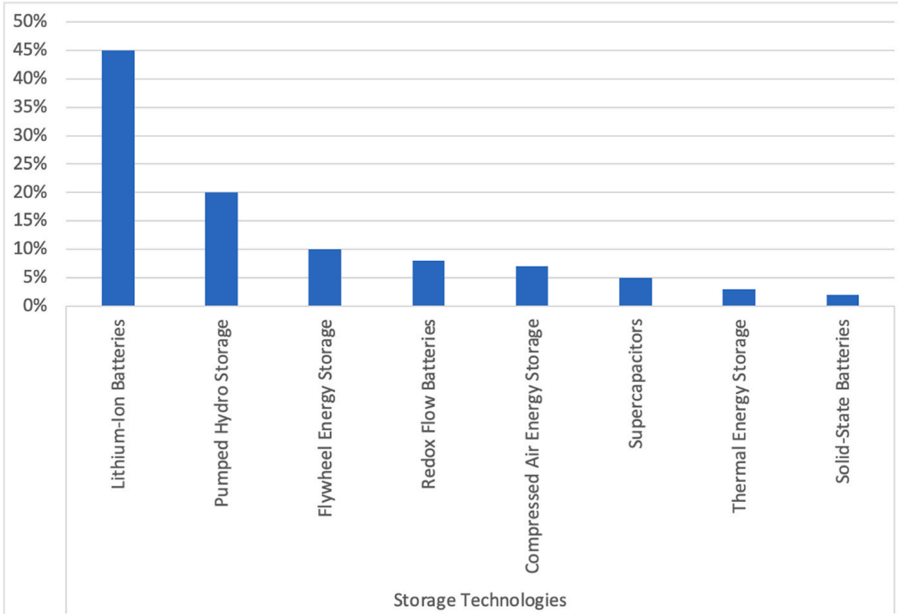


Fig. 12. Summary of the distribution of storage technologies in the reviewed literature.

effective management of variable renewable resources.

One of the pivotal considerations in the selection of storage technologies has been the timescale of operation. Storage systems are often categorised into short-term, medium-term, and long-term storage, aligning with the diverse temporal characteristics of energy demand and renewable energy generation. Short-term storage solutions, such as lithium-ion batteries, are well-suited to rapid-response applications, addressing short-lived fluctuations in energy supply and demand. Medium-term storage options, including pumped hydro storage and compressed air energy storage, serve to smooth out daily or weekly variations. Also, long-term storage solutions such as hydrogen storage and underground thermal storage systems are designed to accommodate seasonal fluctuations in renewable energy availability.

Furthermore, emerging storage technologies have shown significant potential in improving the integration of RESs in RSESs. These innovative solutions, such as flow batteries, novel supercapacitors, and advanced thermal storage, offer unique advantages, including reduced cost and improved efficiency and performance, making them increasingly attractive options.

Storage systems have also been examined within the context of grid interactions. They are envisioned not only as reservoirs for excess renewable energy during times of abundance but also as critical assets for grid reliability, resilience, and stability. Seasonality plays a crucial role, with storage systems effectively bridging the gap between periods of high and low renewable energy production. Their ability to store surplus energy when generation exceeds demand, and discharge it when demand outstrips supply, aids in grid balancing and prevents curtailment of excess renewable energy, ensuring that renewable energy is maximally utilised.

Moreover, much of the literature underscores the capital-intensive nature of storage technologies. While these systems offer value-augmenting benefits such as improved grid reliability, reduced reliance on fossil fuels, and therefore reduced GHG emissions, their initial investment costs remain a significant hurdle. Strategies to reduce these costs, through advancements in materials, manufacturing processes, and economies of scale, are a prominent research focus.

The complementary role of storage technologies in RSESs is also a recurring theme. Rather than viewing storage as a stand-alone solution, many studies emphasise its synergy with other renewable energy components. For instance, combining solar PV with battery storage allows excess daytime energy to be stored and used during night-time hours, thereby enhancing the overall system's reliability. In some instances, overbuilding renewable generation capacity and storing excess energy for later use has been found to be a more cost-effective strategy than curtailment.

In summary, the selection of storage systems in RSESs is guided by a multitude of factors, with the timescale of operation, grid interactions, seasonality, emerging technologies, capital constraints, value augmentation, complementarity, and cost considerations at the forefront of research efforts. As the renewable energy landscape continues to evolve, ongoing innovations in storage technologies hold the promise of assisting in a more resilient, sustainable, and efficient energy future.

6.5. Business models

Within the landscape of RSESs, the exploration of business models has emerged as a pivotal domain. Business models define the strategies and mechanisms through which energy systems are planned, deployed, operated, and monetised. They play a crucial role in shaping the sustainability and viability of renewable energy initiatives.

One notable paradigm shift that has been identified in the literature is the evolution from traditional, grid-centred business models to more decentralised governance models. These contemporary models are equipped to cater to entirely grid-isolated systems or islanded operation modes of grid-connected systems. This shift is partly driven by the increasing recognition of the limitations associated with capital-prohibitive and cost-intensive centralised grid infrastructure.

One innovative business model gaining prominence in recent years is EaaS. The EaaS represents a departure from traditional energy ownership and supply models by offering energy solutions on a service-oriented basis. This approach allows businesses and communities to access renewable energy systems without the need for large upfront capital investments. Instead, they can engage with EaaS providers who deliver clean energy solutions, covering everything from system installation and maintenance to energy management and optimisation.

Collectively, the above review of the underlying business models of RSESs suggests a transition from well-established, grid-centred business models to more decentralised governance models capable of addressing entirely grid-isolated systems or islanded operation modes of grid-connected systems. The EaaS, in particular, stands out as an innovative approach that not only facilitates the integration of renewable energy but also makes it more accessible and financially viable for a broader range of stakeholders. This shift reflects a growing awareness of the need for flexible, adaptive, and economically sustainable models to underpin the renewable energy transition.

7. Recommendations for future research

The extensive review of RSESs reveals several sets of recommendations for future research and development, encompassing various dimensions of this multidisciplinary field.

7.1. Optimal integration of emerging storage technologies

7.1.1. Investigate emerging storage solutions

- Explore the potential of novel energy storage technologies, including advanced battery systems, hydrogen-based storage, and thermal energy storage, within RSESs.
- Evaluate the technical feasibility and financial viability of integrating these emerging storage solutions, particularly in scenarios with pronounced seasonality.

7.1.2. Overcome cost barriers

- Address the significant financial challenges associated with capital-intensive storage technologies by devising innovative financing mechanisms and exploring cost reduction strategies.
- Investigate the role of emerging storage technologies in augmenting system value, with a specific focus on grid interactions and their capacity to offset curtailment of excess renewable energy.

7.2. Innovative business models

7.2.1. Examine innovative business models

- Scrutinise innovative business models, with particular emphasis on the nascent EaaS paradigm, to assess their applicability and scalability within RSESs.
- Examine the potential of EaaS to mitigate the capital-prohibitive nature of renewable energy projects and to deliver value-added services to consumers.

7.2.2. Scalability and regulatory frameworks

- Evaluate the scalability and adaptability of EaaS models across diverse contexts, ranging from remote off-grid communities to urban metropolitan areas.
- Investigate the regulatory and policy frameworks requisite for facilitating the expansion of decentralised energy models, including EaaS, within the broader energy landscape.

7.3. Multi-objective optimisation and advanced meta-heuristics

7.3.1. Utilise advanced multi-objective optimisation

- Utilise cutting-edge multi-objective optimisation techniques to concurrently address a multitude of objectives encompassing cost-effectiveness, environmental impact mitigation, reliability enhancement, system resilience, and so forth within RSESs.
- Explore innovative approaches to balance competing objectives, thereby offering enhanced decision-making support for system design and operation.

7.3.2. Explore advanced meta-heuristics

- Investigate the applicability and efficacy of state-of-the-art meta-heuristic algorithms, particularly when applied to systems that involve peer-to-peer trading and other emerging technologies.
- Conduct rigorous comparative analyses to assess the performance of advanced meta-heuristics across a spectrum of renewable energy integration scenarios, emphasising technical, financial, regulatory, and optimisation dimensions.

7.4. Grid interaction and advanced control strategies

7.4.1. Grid-resilient RSESs

- Undertake research aimed at arming RSESs with advanced grid interaction capabilities, fostering grid resilience during adverse events such as natural disasters or cyberattacks.
- Explore advanced control strategies facilitating the seamless transition of RSESs between grid-connected and islanded modes, ensuring the uninterrupted provision of energy services.

7.4.2. Demand response integration

- Investigate the optimal integration of demand response programs into RSESs, offering real-time adaptability of energy consumption patterns in response to variations in supply.
- Evaluate the potential of demand-side management to diminish peak loads and enhance overall system efficiency, leveraging artificial intelligence (AI) and machine learning (ML) techniques for robust forecasting and optimisation.

7.5. Community-based approaches and social inclusiveness

7.5.1. Community-centric RSESs

- Investigate community-centric approaches in RSES development, recognising the diverse needs and aspirations of local populations.
- Explore the multifaceted impact of community involvement and ownership on the sustainability and social inclusiveness of energy systems, adopting advanced AI and ML methodologies for data-driven insights.

7.5.2. Inclusiveness metrics

- Develop robust metrics and quantitative indicators to gauge the extent of social inclusiveness achieved through RSESs.
- Conduct in-depth assessments of the impact of RSESs on marginalised and underserved populations, informing policy and regulatory frameworks to foster greater equity and accessibility.

The aforementioned recommendations collectively delineate a comprehensive and forward-looking research agenda for the field of RSESs. Addressing these dimensions is crucial for the advancement of energy solutions that are not only more efficient and cost-effective but also environmentally sustainable and socially inclusive. Collaboration among researchers, policymakers, industry stakeholders, and technologists will be instrumental in translating these recommendations into impactful actions that benefit society and contribute to a cleaner and more resilient energy future.

8. Conclusions

In this comprehensive review of RSESs, an extensive exploration of the multifaceted landscape of renewable energy integration, system design, optimisation, and emerging paradigms was undertaken. This systematic review encompassed a diverse array of studies, providing a thorough analysis of the main findings and limitations in the field, and offering best practice insights for the future.

The review commenced by delineating the settings for the studies included in the systematic review, with a focused examination of energy-related concepts. This initial stage aimed at bringing about clarity and coherence within the extensive body of literature under consideration. The subsequent curation process involved meticulous filtration, progressing through distinct phases that aimed to refine the scope and boundaries of the review. Consequently, this systematic approach resulted in the identification of a subset of studies, optimising the precision and relevance of the final analysis.

As the thematic expanse of RSESs was navigated, an array of key findings and limitations has been discussed. The proliferation of renewable energy technologies, including solar, wind, and micro-hydro, and their increasing prominence as cornerstones of sustainable energy systems have been illuminated. These technologies, bolstered by significant cost reductions and technological advancements, are increasingly assisting in a global transition towards renewables.

However, as RSESs evolve, several barriers and challenges have emerged, ranging from technical complexities to financial constraints. The review has revealed that while system cost remains a central criterion for decision-making, a growing body of literature advocates the integration of non-monetary decision criteria, forging the path toward more comprehensive multi-objective optimisation models.

In terms of constraints, the analysis has discerned a separation between short-term operational constraints and long-term planning considerations. While meta-heuristic-based optimisation algorithms have made significant strides in handling operational constraints, further attention is warranted for the systematic study of the role of social and regulatory criteria in RSES design preferences.

Furthermore, the review has highlighted the significance of energy storage systems, elucidating their role in mitigating the variability of renewable sources. The integration of various storage technologies, including batteries, hydrogen-based systems, and thermal energy storage, has also been found as an effective means for the optimal development of RSESs. Yet, the cost-intensive nature of storage technologies remains a challenge, necessitating innovative financing mechanisms and cost reduction strategies.

Synthesising the collective insights derived from this extensive review yields several best practice insights:

- Emerging storage technologies: Thoroughly investigating emerging energy storage solutions, harnessing the potential of advanced battery systems, hydrogen-based storage, and thermal energy storage, with a particular focus on cost-effective integration and addressing seasonality challenges depending on the site's characteristics is critical in the pre-feasibility assessment phase.
- Innovative business models and EaaS: Adopting innovative business models, including the EaaS paradigm, to surmount the capital-prohibitive nature of renewable energy projects can help improve the costing RSESs. Examining the scalability and regulatory frameworks necessary for the widespread adoption of decentralised energy models also remains substantial.
- Multi-objective optimisation and advanced meta-heuristics: Advancing multi-objective optimisation techniques and employing cutting-edge meta-heuristic algorithms to optimally balance competing objectives has a significant potential to facilitate robust decision-making in RSES design and operation.
- Grid interaction and advanced control strategies: Enhancing grid interaction capabilities to bolster the resilience of RSESs and enabling seamless transitions between grid-connected and islanded modes are of particular importance for the widespread adoption of RSESs. Also, advanced control strategies can be leveraged for the optimal demand response integration, whilst making effective use of AI and ML for robust forecasting and optimisation.
- Community-based approaches and social inclusiveness: Developing community-centric approaches and inclusive business models that consider diverse needs and aspirations can also help roll out RSESs. This would also involve developing metrics to quantify social inclusiveness and assess RSES impact on marginalised populations, guiding policy for greater equity.

In conclusion, this review has contributed a new layer of analysis to the mainstream and wider literature on RSESs. It has illuminated current trends, barriers, and prospects in the field, underscoring the importance of comprehensive meta-analyses for deriving novel insights.

Looking ahead, an evolving landscape for RSESs is anticipated, with a growing emphasis on technological innovation, multi-objective optimisation, and enhanced grid interactions. The path forward should involve continued collaboration among researchers, policymakers, industry and community stakeholders, and technologists to translate these insights into actionable strategies that drive the transition to cleaner and more resilient energy systems. It could also involve incorporating real-life examples, project reports, and expert opinions to provide a more practical and applied perspective on the topic. Through concerted efforts and the integration of advanced technologies and approaches, progress can be made in addressing the current energy challenges and paving the way for a sustainable energy future.

CRediT authorship contribution statement

Soheil Mohseni: Conceptualization, Methodology, Data curation, Formal analysis, Investigation, Resources, Software, Validation, Visualization, Writing – original draft. **Alan C. Brent:** Supervision, Project administration, Formal analysis, Investigation, Resources, Validation, Writing – review & editing.

Declaration of competing interest

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

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.esr.2025.101640.

Data availability

Data will be made available on request.

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