

Review

Overcoming Technical and Operational Barriers in Low-Voltage Mini-Grids: Two Decades of Research Trends, Progress, and Pathways for Accelerated Rural Electrification (2005–2025)

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Abstract

Low-voltage mini-grids play a crucial role in expanding electricity access for rural and remote communities. However, they continue to face technical and operational barriers that hinder their performance and reliability. This study reviewed the evolution of research on technical challenges in low-voltage mini-grids from 2005 to 2025. Using the PRISMA approach, data were extracted from the Scopus database, yielding 155 publications for bibliometric analysis. Bibliometrix in R Studio was used to examine publication trends, geographical contributions, and thematic evolution, while qualitative synthesis identified key engineering and operational constraints. The findings revealed a steady increase in research outputs since 2020, driven by global policy commitments, including Sustainable Development Goal 7 and the Paris Agreement. Persistent technical barriers include voltage and frequency instability, inadequate power quality monitoring, inefficient integration of energy storage, poor control coordination, and limited system design optimisation. African nations contribute less to global research despite being most affected by energy poverty, highlighting capacity and funding gaps. The study highlights the need for integrated solutions combining smart control, hybrid storage, and grid-interconnection technologies to enhance resilience and reliability. For policymakers and practitioners, the findings advocate for investment in research, capacity building, and locally tailored technical standards designed for resource-constrained contexts. This review provides a comprehensive evidence base to guide future research and policy directions aimed at achieving sustainable, technically robust, and financially viable mini-grid systems for universal energy access.

Keywords: mini-grids; technical challenges; energy access; rural electrification; power quality; sustainable development



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1. Introduction

Access to reliable, affordable, and modern energy remains one of the most pressing global challenges in rural and remote regions of developing countries [1,2]. Although global electrification has reached about 92%, over 670 million people still lack electricity (85% in rural areas) [3,4]. Sub-Saharan Africa (SSA) bears the brunt of this deficit. Recent data indicate that only 48% of Africans overall have access to electricity (up from 33% in 2010), with rural access at ~28% [2]. In this context, extending the main grid to remote, low-density communities is often prohibitively expensive or technically impractical, which has spurred interest in off-grid solutions.

Renewable-based mini-grids, which are small local power systems (typically 10 kW–10 MW) operating at low-voltage distribution levels (≤ 400 V AC) and serving villages or clusters of communities, are now widely promoted as a key strategy for reaching off-grid populations [5,6]. The falling costs of solar PV and batteries have also made hybrid mini-grids cost-effective where grid extension is infeasible [7]. Similarly, international initiatives (e.g., the World Bank/AfDB's "Mission 300") and major funding programmes have surged, demonstrating the view that solar- and diesel-powered mini-grids are essential to meet Sustainable Development Goal 7 on affordable, reliable, and modern energy [8]. For example, recent estimates report that in 2021, approximately 1100 new rural mini-grid systems (with a capacity of approximately 80 MW) were deployed worldwide, with South Asia leading annual installations, followed by SSA [9]. In SSA alone, roughly 11 million mini-grid connections are now operational [2]. These trends highlight the role of mini-grids in electrifying remote communities.

At the same time, however, substantial technical and operational barriers have persisted at the low-voltage (LV) distribution level, especially in African mini-grids [10]. Many existing systems were originally sized only for basic lighting and small loads, and have struggled to adapt to growing demand and the integration of power-hungry appliances [11,12]. Studies have repeatedly noted that LV mini-grids often face severe voltage regulation problems (e.g., excessive voltage drops or rises), feeder capacity constraints, power quality issues, and frequent reliability disruptions [11]. For instance, adding new generations (such as rooftop solar) or loads (such as electric cooking) to a typical rural network can exacerbate voltage imbalances and overload transformers, leading to unstable or out-of-spec voltages. These effects are especially critical in DC/LV systems, where resistive voltage drop limits the geographical footprint of the DC mini-grid [13].

Similarly, field surveys have found that insufficient maintenance and harsh environments (e.g., dust, heat) cause battery failures and inverter faults, reducing uptime [14]. In a recent study of two Namibian mini-grids, system output declined over time due to poor maintenance and battery overheating, resulting in one mini-grid becoming undersized as demand increased [12]. Such issues mean that many LV mini-grids in practice only deliver Tier 1 and Tier 2 level service (basic lighting, television, air circulation, and phone charging), with high losses and low revenue bases [15].

Several authors have reviewed different aspects of mini-grids for rural electrification in developing regions. Sada et al. [16] conducted a scientometric analysis examining research trends and patterns in electrification planning over a five-decade period. Odoi-Yorke et al. [17] conducted a bibliometric analysis to assess the trends in mini-grids for rural electrification from 2003 to 2023. Moner-Girona et al. [18] investigated cost structures and transparency issues in PV/hybrid mini-grid projects across SSA. In the work of Antonanzas-Torres et al. [1], the authors described the current status and future challenges of off-grid mini-grids in West Africa. Come Zebra et al. [5] analysed hybrid renewable energy systems designed to address the intermittent nature of renewable resources.

Other studies include Fajardo et al. [19], who critically examined business models and financing mechanisms for mini-grid development in SSA. They identified access to finance as a major barrier to expansion. The authors argued that no universal solution exists for mini-grid business models in the region. Akinlabi and Oladokun [20] reviewed interconnected mini-grid solutions and viable business models in Nigeria's post-reform electricity sector. Babayomi et al. [2] provided a comprehensive review of the deployment status of off-grid renewable mini-grids in SSA. Kemausuor et al. [21] reviewed energy planning tools for deploying on-grid and off-grid renewable technologies across Africa. Gill-Wiehl et al. [22] analysed community participation in private mini-grid projects and their impact on sustainability. Bhattacharyya [23] explored whether mini-grids can effectively serve base-of-the-pyramid markets and associated deployment challenges. Frimpong et al. [24] reviewed optimisation approaches for estimating configuration size, cost, and reliability of hybrid renewable energy systems.

Despite extensive reviews of mini-grids, studies addressing the technical challenges and operational constraints of low-voltage systems are limited. This study fills that gap by employing both bibliometric and systematic review approaches to comprehensively identify and synthesise the key technical issues and operational limitations affecting low-voltage mini-grids. To achieve this, the study addresses the following research questions: RQ1: How has research on low-voltage mini-grids evolved over time and across countries? RQ2: Who are the key contributors, and what are the collaboration networks within this research domain? RQ3: What are the dominant and emerging technical themes in low-voltage mini-grid studies? RQ4: What major technical and operational challenges have been reported in low-voltage mini-grids? RQ5: What research gaps and future directions can be identified from existing studies? The study findings provide critical insights into the technical challenges, operational constraints, and emerging research trends in low-voltage mini-grids. It also provides valuable guidance for policymakers, developers, investors, and researchers.

The remainder of this paper is organised as follows: Section 2 describes the bibliometric and systematic review methodologies employed in this study. Section 3 presents the results of the bibliometric analysis, highlighting publication trends, key contributors, and collaboration networks. Section 4 discusses the findings from the synthesis of existing studies in the literature, focusing on the technical and operational aspects of low-voltage mini-grids. Section 5 provides a summary of thematic insights and outlines directions for future research. Finally, Section 6 concludes the paper, providing key recommendations and a way forward for relevant stakeholders.

2. Methodology

The study employed both quantitative bibliometric analysis and qualitative systematic analysis to address its goal. Figure 1a illustrates the bibliometric analysis process. The study retrieved data from the Scopus database, which is known for its extensive coverage of peer-reviewed scientific literature and its reliability in bibliometric and systematic review studies [25]. Similar studies have also relied exclusively on Scopus data, as is the case in this study [26–31]. The search strategy was carefully developed using a combination of keywords and Boolean operators to ensure inclusiveness and relevance to the topic under investigation. The search query comprised the following: ("mini grid*" OR "mini-grid*") AND ("technical challenge*" OR "technical constraint*" OR "technical limitation*" OR "technical barrier*" OR "engineering challenge*" OR "operational challenge*" OR "system reliability" OR "voltage stability" OR "frequency stability" OR "power quality" OR "harmonic distortion" OR "voltage drop" OR "protection coordination" OR "fault detection" OR "energy management" OR "control system*" OR "storage integration"

OR "inverter control" OR "system monitoring" OR "telemetry" OR "load management" OR "system performance" OR "grid stability" OR "islanding" OR "synchronisation" OR "power losses" OR "distribution losses"). The search was limited to the period 2005–2025 to capture two decades of research progress and evolving trends in the field of low-voltage mini-grids. The initial search yielded 156 documents across all subject areas. To enhance the quality and focus of the dataset, filters were applied to include only articles, conference papers, reviews, and book chapters, resulting in a dataset of 155 publications. Further refinement was made by restricting the selection to English-language publications, as these dominate scientific communication and ensure consistency in content interpretation. The final dataset, extracted on November 6, 2025, in CSV format, was used for bibliometric review analyses.

The bibliometric analysis was conducted using the Bibliometrix package in RStudio (version: 2026.01.0+392), as shown in Figure 1a. Bibliometrix, developed by Aria and Cuccurullo [32], is a widely used software for quantitative bibliometric analysis. This study focused on the following analyses: (i) publication trends in annual article production to determine research growth and temporal evolution; (ii) country-level research contributions and international collaboration networks to identify global participation and partnership patterns; (iii) keyword analysis to reveal dominant themes, research hotspots, and emerging technical challenges; and (iv) thematic evolution and factorial analysis of keywords to visualise conceptual structures and topic interrelations over time.

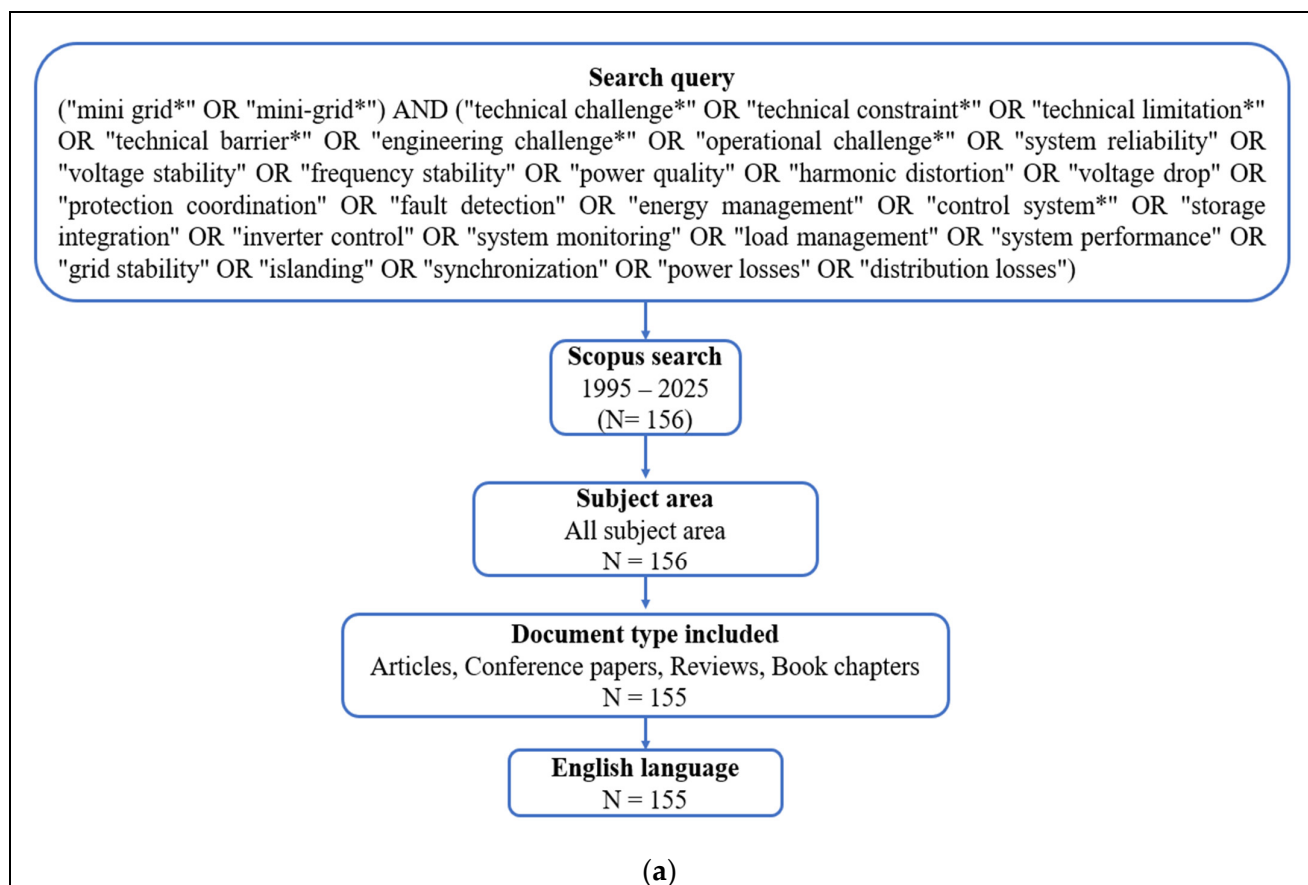


Figure 1. Cont.

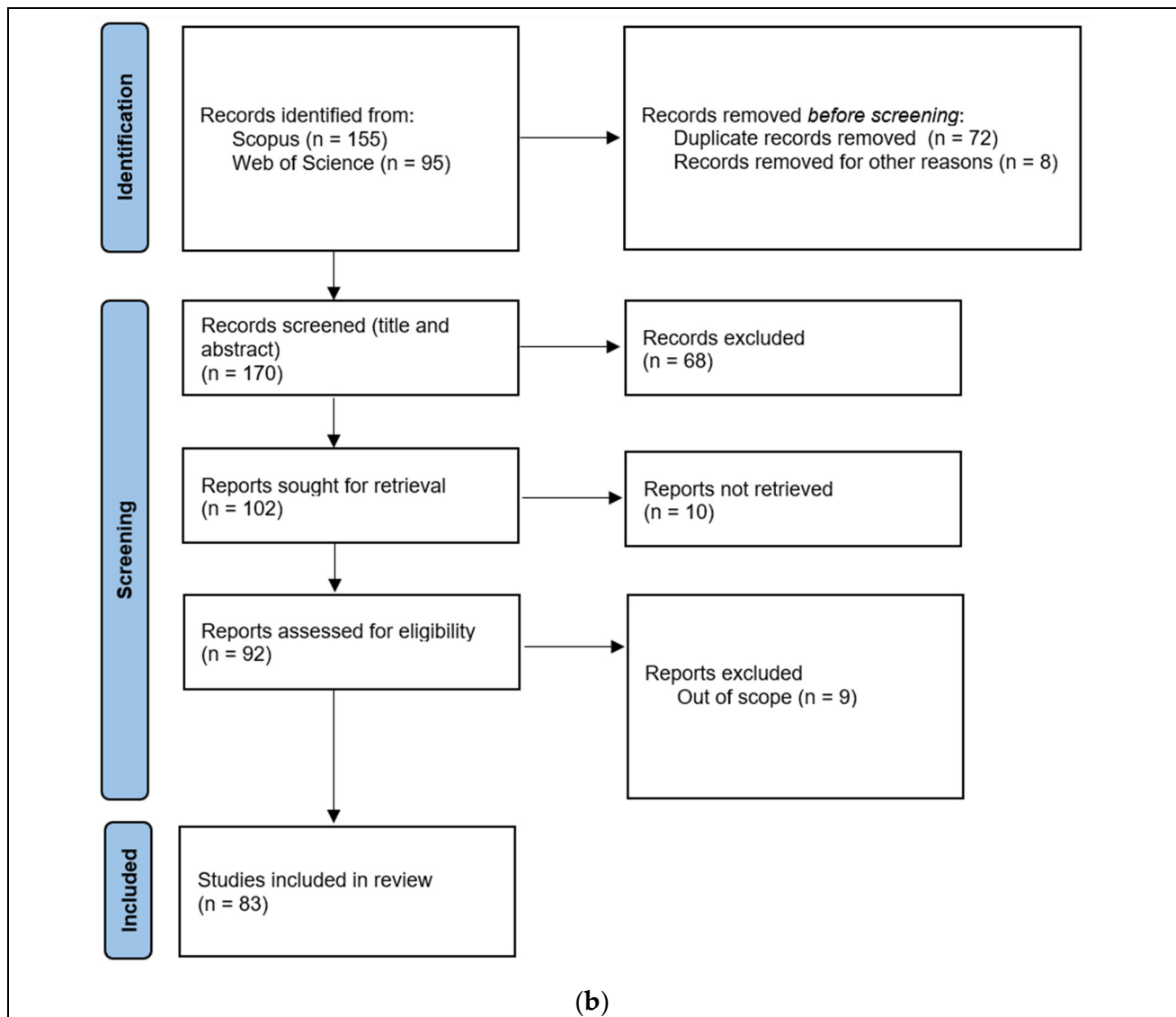


Figure 1. Methodological framework adopted (a) Bibliometric analysis using Bibliometrix in R-Studio (b) PRISMA guidelines showing the number of records identified, screened, excluded, and finally included for full-text review and analysis [33].

Following the bibliometric assessment, a systematic review was conducted, as illustrated in Figure 1b. The review process followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines and consisted of four sequential stages: identification, screening, eligibility assessment, and inclusion. During the identification stage, a total of 250 records were retrieved from two databases, namely Scopus ($n = 155$) and Web of Science ($n = 95$). These records were imported into reference management software for data cleaning. Prior to screening, 72 duplicate records were removed, along with a further 8 records excluded for other reasons, resulting in 170 unique records for screening.

In the screening stage, titles and abstracts of the 170 records were independently reviewed to assess their relevance to the study objectives. At this stage, 68 records were excluded due to lack of relevance, leaving 102 reports sought for full-text retrieval. Of these, 10 reports could not be retrieved, resulting in 92 full-text articles assessed for eligibility. The eligibility stage involved a detailed full-text evaluation focusing on methodological rigour, relevance, and substantive contribution to the study scope. As a result, 9 articles were excluded for being out of scope. It is worth mentioning that any disagreements between

the two independent reviewers during the screening and eligibility stages were resolved through discussion and consensus, with a third reviewer consulted where consensus could not be reached. Finally, 83 studies met all inclusion criteria and were included in the final systematic review and synthesis. These final studies formed the evidence base for analysing and categorising the key technical challenges across multiple thematic areas as follows (i) power quality, stability, and frequency regulation challenges in mini-grids; (ii) energy storage integration, battery management, and system reliability in mini-grids; (iii) control system architecture, coordination, and automation challenges; (iv) renewable energy integration, variability management, and curtailment; and (v) system design, planning, and techno-economic optimisation.

3. Results and Discussion

3.1. Trend in Annual Publications

Figure 2 shows the publication trends in annual article production from 2005 to 2025. It can be observed that the early period from 2005 to 2008 recorded minimal research activity, with only 2 to 4 publications in total. This period demonstrates the early stage of mini-grid deployment and limited academic attention to their technical and operational complexities. A gradual increase occurred between 2009 and 2016, during which annual publications varied from 3 to 11 articles, suggesting keen interest in mini-grids as viable electrification solutions for underserved populations. This growth phase coincides with the United Nations' declaration of 2012 as the International Year of Sustainable Energy for All and the subsequent establishment of the Sustainable Energy for All initiative [34], which could catalyse global dialogue around distributed renewable energy systems.

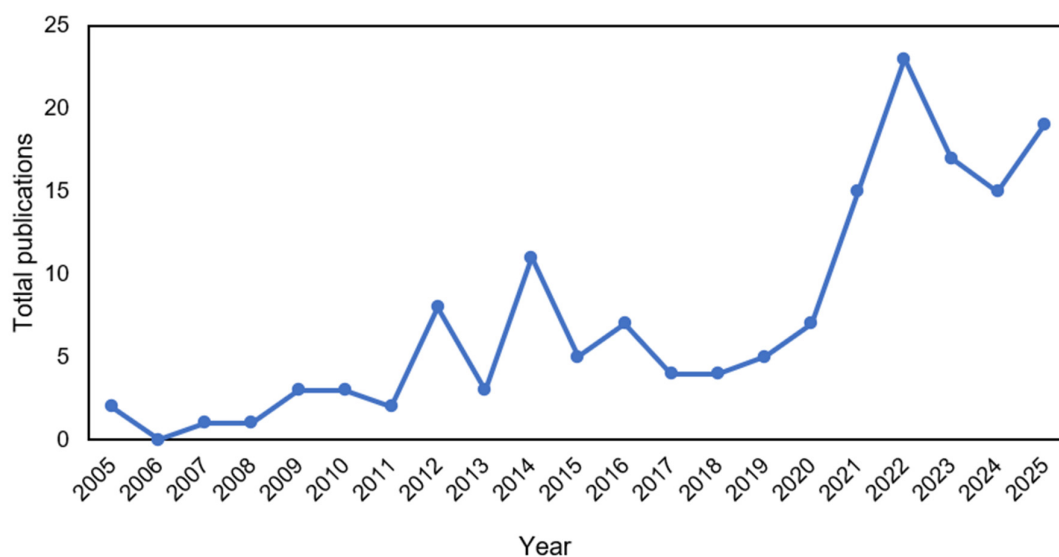


Figure 2. Trend in annual article production.

As shown in the figure, the transition point in research intensity occurred around 2020, when the number of annual publications increased to 7 articles and afterwards surged to 15 in 2021, 23 in 2022, and remained elevated at 15 to 19 articles through 2025. It is worth noting that this research growth pattern could be due to several critical policy developments and international commitments. For example, the adoption of the United Nations Sustainable Development Goals (SDG) in 2015, mainly SDG 7, which targets universal energy access by 2030 [35], established a global framework that prioritised mini-grid solutions for remote and rural electrification. In addition, the Paris Agreement's goal of limiting global temperature rise to well below 2 °C while pursuing efforts to

reach 1.5 °C [36] could accelerate global interest in renewable energy, thereby accelerating research on decentralised renewable energy systems, and the African Union's Agenda 2063 could provide additional motivation for mini-grid research and deployment. Furthermore, the COVID-19 pandemic paradoxically could have enhanced research interest, as energy access became an essential infrastructure for healthcare delivery and economic resilience in isolated communities. Moreover, finance from institutions such as the World Bank, the African Development Bank, and bilateral donors, allocated explicitly for mini-grid programmes, could have established an environment that requires rigorous technical and operational analysis.

The sustained research output from 2021 through 2025, despite some year-to-year fluctuation, indicates that mini-grid research has shifted from an early-stage field to a fully developed field within the energy systems domain. This growth demonstrates both the global scaling of mini-grid deployments and the growth of operational experience, revealing persistent technical challenges that require ongoing investigation. The trends in research growth imply that, as mini-grids are central to achieving universal electrification targets, continued research attention to resolving technical and operational constraints will remain essential for optimising system performance, ensuring financial sustainability, and maximising socio-economic impacts in vulnerable communities.

3.2. Geographical Research Contributions and Collaboration Network

Figure 3a displays the research contribution per country. The results show that the United Kingdom (UK) is the leading contributor, accounting for 10.7% of the global research output, followed by India (8.4%) and Canada (5.8%). It is evident that African countries make a significant contribution to the global research output, with Ghana (4.6%), South Africa (5.1%), and several other nations making contributions to this research domain. However, the dominance of developed nations, especially the UK, India, and Canada, raises critical questions about research capacity, funding mechanisms, and policy frameworks that enable sustained scientific inquiry in this vital sector. The UK's leadership can be attributed to robust research infrastructure supported by policies such as the Research Excellence Framework (REF) and funding through UK Research and Innovation (UKRI), which prioritises energy access and renewable technologies. Likewise, Innovate UK has supported mini-grid technologies through funding and collaborations, including programmes like the Energy Catalyst Briefing and Brokerage Events [37]. This support involves connecting innovators with investment, often fostering partnerships between academia and industry to develop and commercialise new technologies. India's contributions could be attributed to the Dayal Upadhyaya Gram Jyoti Yojana (DDUGJY) and the National Smart Grid Mission, which may have catalysed research funding through institutions such as the Ministry of New and Renewable Energy (MNRE) and the Department of Science and Technology. The DDUGJY aimed to strengthen rural electricity distribution by separating feeders, upgrading networks, expanding rural electrification, and improving metering to ensure a reliable, quality, and accessible power supply for rural communities [38].

For African countries, the case for increased research contribution is urgent. Despite facing the world's most severe energy access challenges, with over 600 million people lacking access to electricity [39], the contributions of African nations represent only a fraction of the global research output in this field. Ghana's contributions (4.6%) can be attributed to initiatives such as the Ghana Energy Development and Access Project, which aimed to provide increased access to affordable, reliable and adequate electricity [40]. In addition, Ghana's Renewable Energy Masterplan, which aimed to deploy 4.8 MW of hybrid mini/micro-grids by 2021–2025 [19], could have accelerated research interest in the country. Nigeria, despite its high energy deficit, shows a lower contribution (2.2%). However, the

Rural Electrification Agency's Mini-Grid Regulations (2016) [41] is a key policy framework that could accelerate research if paired with dedicated funding mechanisms. It is worth noting that the observed research gap in African countries may be driven by several structural challenges, including limited research funding, constraints related to publication fees and journal subscriptions, inadequate laboratory infrastructure, and weak linkages between policy implementation and academic inquiry.

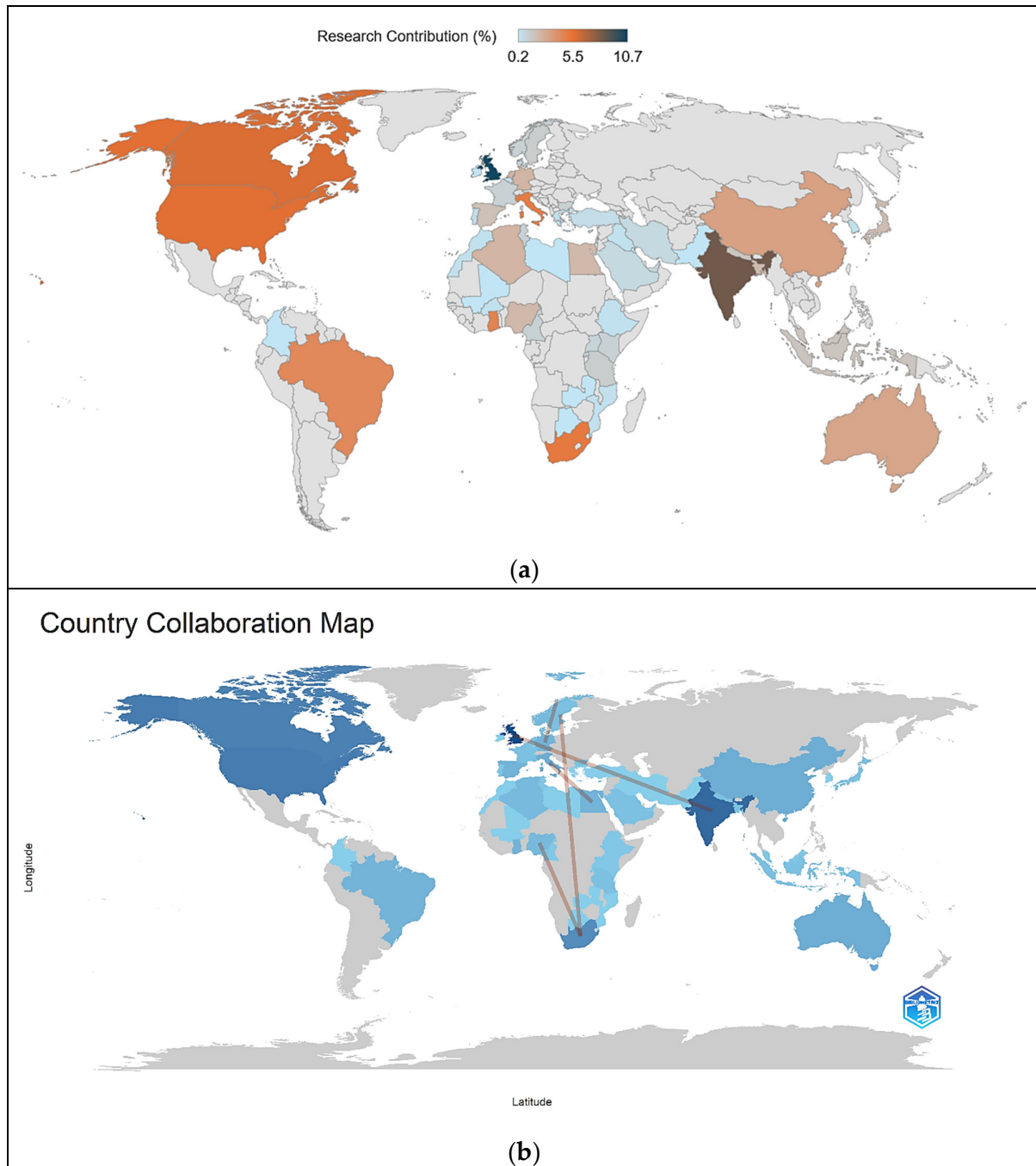


Figure 3. (a) Geographical research contributions and (b) Research collaboration network among countries.

Conversely, this implies not a deficit of need or potential, but rather an opportunity for transformative investment. Thus, improved research capacity in African nations would generate context-specific solutions addressing unique challenges, such as payment systems adapted to informal economies, hybrid systems resilient to extreme weather variability, and community ownership models that capture varied governance arrangements. To

bridge this gap, African nations must prioritise the establishment of dedicated research funds, modelled after India's MNRE or the UK's UKRI, strengthen South-South research collaborations, and implement policies mandating research components in all mini-grid deployment projects. This approach will transform energy access challenges into catalysts for indigenous innovation and sustainable development.

The country collaboration map, which illustrates the geographical distribution and interconnectedness of research networks, is displayed in Figure 3b. It is worth noting that the colour gradient, ranging from light blue to dark blue, denotes the varying degrees of research activity or collaboration frequency, with darker shades indicating higher contribution levels in mini-grid research. Countries rendered in grey have no research contributions in this domain during the study period. The connecting lines traversing the map depict collaborative linkages between nations, with South Africa emerging as the primary hub of collaboration, as evidenced by multiple lines radiating from the southern African region to various global partners. This network structure emphasises several critical implications for the mini-grid research domain. For example, the collaboration between developed nations (North America, Europe) and select developing countries suggests a North–South research paradigm, where resource-rich institutions in developed countries partner with implementation-context regions in the Global South. The intense blue colouration in North America (Canada and the USA), parts of Europe (notably the UK), India, and Australia indicates that these regions serve as primary knowledge production centres, likely possessing advanced research infrastructure, substantial funding mechanisms, and established academic institutions specialising in off-grid electrification technologies. South Africa's position as a collaboration nexus is significant due to its dual role as both an African nation facing energy access challenges and a relatively advanced economy with established research capacity, thereby serving as a bridge between African countries and global research networks.

However, the map also shows concerning gaps: large portions of sub-Saharan Africa, Central Asia, and parts of Southeast Asia remain grey or light blue, suggesting limited research contribution despite severe energy poverty in these regions. The collaboration lines mostly connect high-income and upper-middle-income countries, indicating that research partnerships may not adequately reach the least developed countries, where mini-grid solutions are most urgently needed. This spatial distribution raises questions about knowledge asymmetries, research agenda-setting power, and the extent to which locally generated insights from energy-poor regions influence global mini-grid discourse. The concentration of collaborations among a small cluster of countries may lead to the homogenisation of research priorities, potentially overlooking context-specific technical challenges and operational constraints unique to underrepresented regions.

Furthermore, the scarcity of South-South collaboration lines (connections between developing countries) suggests missed opportunities for peer learning and technology transfer among nations facing similar socioeconomic and infrastructural contexts. The implications are clear: although existing research networks have generated valuable knowledge, there is an urgent need to democratise mini-grid research through capacity building in underrepresented regions, fostering more equitable South-South partnerships, and ensuring that collaboration frameworks genuinely incorporate perspectives and priorities from communities most affected by energy poverty, thereby creating a more inclusive and geographically diverse research ecosystem.

3.3. Word Cloud of the Most Occurring Keywords

Figure 4 illustrates the dominant themes and research priorities within the dataset. The emergence of “mini-grid” and “microgrid” as the largest terms confirms these decentralised

[illegible]

The size of “rural electrification” highlights the geographical and socio-economic context that drives the deployment of mini-grids. These systems have become technically and economically viable solutions for extending electricity services to remote populations. Conventional grid extension remains excessively expensive or logistically impractical in such contexts. Agbo et al. [42] reported that conventional grid extension is economically unfeasible for remote areas. This is due to challenging terrain, dispersed populations, and low demand. Similarly, Nossek and Berthelemy [43] concluded that mini-grids are popular for electrifying rural locations, based on an examination of 144 mini-grids deployed in Burkina Faso and Madagascar between 2015 and 2020. Aluko et al. [44] highlighted Rwanda’s challenges in electrification, noting that private investments are essential for rural electrification.

<https://doi.org/10.3390/en19040933>

The appearance of “diesel-driven generators,” “diesel genset,” and “biomass” in the figure suggests hybrid configurations. Most hybrid renewable energy systems (HRES) combine renewable and conventional generation sources, addressing the intermittency challenges inherent to renewable resources. HRES provide necessary system reliability and power quality assurance for mini-grid operations. For this case, Rangel et al. [48] developed a cost optimisation model for diesel/PV/battery microgrids in Tanzania. The authors found that each electricity demand scenario requires specific diesel generators, influenced by PV and battery units, with a levelized cost of energy (LCOE) ranging from £0.42 to £0.45/kWh. Al-Bayati et al. [49] found that integrating solar PV and wind turbines with diesel generators provides a cost-effective solution, achieving an LCOE of \$0.123/kWh for rural electrification in Iraq. See et al. [50] found that PV/wind turbine/battery/diesel HRES configurations achieved a LCOE of \$0.198/kWh for Malaysia’s Malawali island. Odoi-Yorke et al. [51] concluded that solar PV/biogas/battery systems for Ghana’s remote communities outperform diesel-only alternatives in terms of cost and emissions reductions.

Similarly, the emergence of terms such as “power quality” and “energy storage” reveals critical technical challenges. These challenges confront mini-grid operators and researchers in decentralised electrification contexts. Power quality issues include voltage fluctuations, frequency deviations, and harmonic distortions [52–55]. These are persistent operational constraints that directly impact consumer satisfaction and the lifespan of equipment. This impact occurs due to the voltage-sensitive nature of modern appliances and productive-use equipment. The emphasis on energy storage technologies in the word cloud, including “battery energy storage” and “battery storage,” suggests their indispensable role. Battery energy storage systems (BESS) manage renewable energy variability, facilitate load balancing, and ensure a continuous power supply during periods of insufficient generation [56–58]. This focus is especially salient, as battery systems typically account for 35% to 45% of total capital expenditure [59]. BESS encounters challenges related to degradation, replacement costs, and thermal management in tropical climates [60–63]. In view of this, Schulte et al. [64] reported that a forecast-based charging strategy prolongs lithium-ion battery lifetime by reducing average battery state-of-charge by 20%. However, this reduction occurred without causing power outages for the mini-grids. Hassane et al. [65] showed photovoltaic/battery systems had optimal net present costs in multiple villages.

The appearance of terms such as “smart grid,” “energy management,” “demand-side management,” and “demand response” indicates areas of investigation by researchers in mini-grid research. In this context, operational optimisation through intelligent control systems and consumer engagement strategies is essential for mini-grid viability. These demand-side interventions address the fundamental challenge of low capacity utilisation plaguing rural mini-grids. Residential consumption patterns typically exhibit sharp evening peaks with minimal daytime demand. Ray and Chakraborty [66] revealed that demand response improves mini-grid economics, reducing investment by 62%, energy costs to \$0.23, and also brings 186 million people within affordable access. Wassie and Ahlgren [67] reported that supply side factors, appliance factors, and location-specific factors have a greater influence on demand than income in Ethiopian off-grid PV mini-grids. Ihirwe et al. [68] concluded that peak shaving in solar PV mini-grids with large critical loads enables affordable electricity, while hybrid systems and demand creation support sustainable operations for firms. Afonaa-Mensah et al. [69] concluded that integrating agro-processing loads into Ghanaian mini-grids improved the load factor, increased solar correlation, and reduced the levelized energy costs. Gelchu et al. [70] demonstrated that the implementation of demand-side management in household and productive use categories reduced the levelized energy costs by 45.8% and 20.7%, respectively. Youssef et al. [71] demonstrated that optimisation algorithms in smart homes with mini-grids achieved elec-

tricity cost reductions of 76% through strategic storage and trading decisions. Dibaba et al. [72] confirmed that demand response programmes reduce system costs and enhance battery storage lifespan in off-grid microgrids. Opoku et al. [73] identified redundant energy ranging from 56.98 to 119.86 kWh daily on mini-grids, which could support cooking applications through thermal batteries. Keddar et al. [74] proposed smart battery management systems that regulate charging rates to alleviate network constraints and increase service quality. Juma et al. [75] emphasised that energy management systems reduce system downtime and improve operational reliability in Malawian mini-grids. Nanda et al. [76] highlighted that intelligent energy management enables optimal micro-grid operation through real-time demand-supply monitoring and predictive scheduling. Alves Dos Reis et al. [77] demonstrated that effectively managing hybrid microgrids enhances reliability and service continuity in distribution networks.

The presence of terms such as “sustainability,” “resilience,” and “energy access” demonstrates broader developmental objectives. These objectives underpin the deployment of mini-grids, extending beyond mere technical performance and economic viability. They also include community empowerment and climate adaptation considerations for sustainable development. The sustainability literature examines multiple aspects of mini-grid viability across economic, social, and environmental contexts. Katre et al. [78] assessed community-owned systems using novel scoring frameworks that evaluate institutional, financial, and technical capacities over extended operational periods. Lesala and Mukumba [79] demonstrated that meaningful community participation across governance, technical engagement, economic inclusion, and social domains strengthens local ownership, system functionality, and long-term viability. The resilience discourse addresses climate-induced vulnerabilities affecting centralised infrastructure and energy poverty in low-income regions. Okesiji [80] reported that decentralised renewable energy systems provide cost-effective, climate-resilient, and scalable alternatives that leverage locally available resources. Abuzayed et al. [81] show solar and wind energy diversify energy portfolios and reduce hydropower dependence during drought periods. The energy access agenda emphasises equitable electrification strategies that combine grid extension with decentralised solutions, such as solar home systems and mini-grids. Abuzayed et al. [81] found that these approaches offer lower per capita costs while achieving universal access targets. Gollwitzer et al. [82] conceptualised mini-grid electricity as a common-pool resource, drawing lessons from the natural resource management literature. Suryani and Dolle [83] identified critical success factors, including the selection of remote sites with clustered settlements, continuous community involvement from planning through project cycles, life cycle thinking, autonomous system functioning, and contingency planning for grid arrival.

Additionally, terms such as “off-grid electrification,” “distributed generation,” and “autonomous power systems” underscore the paradigm shift. This shift moves from centralised to decentralised energy architectures, signifying a fundamental reconceptualisation of electrification pathways. These pathways operate in resource-constrained contexts where traditional grid extension proves impractical. Sayani et al. [84] found that considering demand growth and using multi-stage mini-grid sizing in rural India can reduce costs by 12%, enabling gradual expansion over single-stage approaches. Ukwuoma et al. [85] found that stand-alone systems in Nigeria’s Kwalita Village achieved a net present cost of \$209,402, an energy cost of \$0.228/kWh, a renewable fraction of 99.8%, and an emissions reduction of 98.7%. Sawadogo et al. [86] found that solar mini-grid feasibility in Burkina Faso’s Nienega-Mossi community improved with GIS-based load profiling and Particle Swarm Optimisation, reducing LCOE while ensuring reliability. The frequent appearance of terms such as “inverter,” “induction generator,” and “electrical distribution network” demonstrates sustained research attention on the design, optimisation, and integration

of key system components within mini-grids. This focus is characteristic of a relatively mature technology, where ongoing work seeks to refine performance, reliability, and system coordination rather than address fundamental feasibility. Furthermore, the use of terms such as “developing country” and “Sub-Saharan Africa” explicitly situates this research. The research exists within specific geographical and developmental contexts where energy poverty remains a pressing issue. Mini-grids serve as critical infrastructure for achieving SDG 7 in these regions.

3.4. Thematic Evolution and Factorial Analysis of Keywords

Figure 5 illustrates the historical progression and interconnectedness of research themes across three distinct periods: 2005–2018, 2019–2022, and 2023–2025. The figure employs a Sankey-style diagram, where box sizes denote the thematic occurrence within each period, colours denote distinct research themes, and connecting lines trace the evolution and transformation of topics across temporal boundaries. It can be observed that during the foundational period (2005–2018), research concentrated on “minigrids” as the dominant theme, accompanied by emerging interests in “smart grid,” “off-grid,” “power quality,” and “mini-grid” technologies. The smaller box sizes suggest an early stage in the mini-grid domain, characterised by a limited publication volume and narrow thematic diversity. Notably, “rural electrification” emerged as a distinct but comparatively minor theme, indicating limited attention to developmental contexts during this early phase.

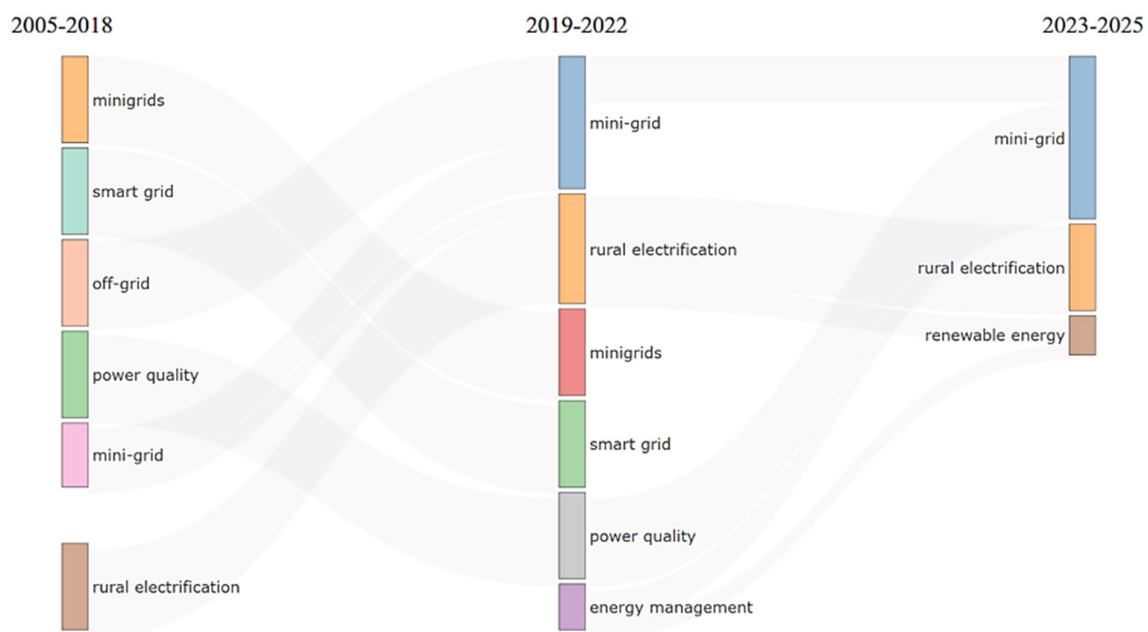


Figure 5. Thematic evolution of keywords.

The intermediate period (2019–2022) saw thematic expansion and consolidation, evidenced by significantly larger box sizes across multiple themes. “Mini-grid” appeared as a dominant research focus, demonstrating standardised terminology adoption within the academic community. The significance of “rural electrification” increased, demonstrating awareness of mini-grids as critical infrastructure for addressing energy poverty in underserved regions. The persistence of “minigrids,” “smart grid,” “power quality,” and “energy management” as distinct themes reveals continued attention to technical challenges, whilst the connecting lines reveal thematic continuity and evolution from the previous period. The emergence of “energy management” as a new theme suggests that researchers have developed an increased attention to operational optimisation research. The most recent

period (2023–2025) exhibits further thematic concentration, with “mini-grid” maintaining dominance, accompanied by an emphasis on “rural electrification” and the emergence of “renewable energy” as a distinct, major theme. This thematic shift implies that the contemporary research domain focuses on sustainable generation technologies and the challenges of their integration. The connecting lines indicate a clear lineage from previous periods, with “renewable energy” drawing from multiple antecedent themes, suggesting a synthesis of earlier disparate research streams into cohesive, renewable-focused investigations.

It is worth mentioning that the thematic evolution highlights several critical implications for the field’s development. First, the consolidation around “mini-grid” terminology indicates growth and standardisation of conceptual frameworks. Second, the progressive elevation of “rural electrification” highlights the alignment between technical research and developmental objectives. Third, the recent emergence of “renewable energy” as a distinct major theme demonstrates the paradigm shifts toward decarbonised mini-grid configurations. The persistent presence of “power quality” across all periods highlights enduring technical challenges requiring sustained research attention, while the evolution from generic “smart grid” concepts to specific “energy management” approaches demonstrates technical sophistication and operational focus in addressing mini-grid constraints.

The factorial analysis (Figure 6) presents a two-dimensional representation of keywords, where the horizontal and vertical axes denote the first two principal components capturing the maximum variance in the dataset. The spatial proximity of terms indicates their co-occurrence patterns and thematic associations within the literature. It can be observed that the cyan-shaded region in the upper portion of the plot comprises a densely populated cluster of interconnected keywords, including “renewables,” “minigrid,” “grid forming,” “bess” (battery energy storage systems), “diesel genset,” “diesel hybrid mini grid,” “grid support mode,” and “grid forming mode,”. This cluster shows a coherent thematic domain centred on hybrid generation configurations and operational modes. This clustering demonstrates that contemporary mini-grid research emphasises the integration of renewable energy sources with conventional diesel generation and energy storage systems, addressing the technical challenge of managing intermittent renewable resources and maintaining system stability and reliability. The positioning of “renewables” at the extreme right of this cluster, with the highest concentration of associated terms, underlines its centrality as the dominant generation paradigm. At the same time, the proximity of “bess” and operational mode descriptors suggests the critical role of energy storage in enabling flexible system operation between grid-forming and grid-support configurations.

In contrast, the lower right quadrant displays a spatially distinct cluster rendered in coral-pink tones, comprising “electrical distribution network,” “emergency control,” “distributed small generation,” and “automation.” This separation along both dimensional axes indicates a fundamentally different thematic orientation focused on network architecture, control systems, and operational management rather than generation technologies. The factorial separation suggests that research addressing distribution network design, emergency response protocols, and automated control systems falls into a different intellectual domain, with limited co-occurrence with generation-focused studies. This reveals a potential fragmentation in the literature, where generation planning and distribution system operation are investigated independently rather than holistically. This bifurcation has significant implications for mini-grid development, as it suggests that technical challenges related to generation integration and those concerning distribution network stability are often addressed in isolation, potentially hindering the development of comprehensive solutions that optimise both generation dispatch and network operation simultaneously. To address this gap, integrated methodological frameworks that couple long-term techno-economic optimisation with short-term dynamic control simulations are essential. Such frameworks should

combine multi-year capacity expansion models with high-resolution operational simulations that capture voltage dynamics, frequency regulation, and protection coordination.

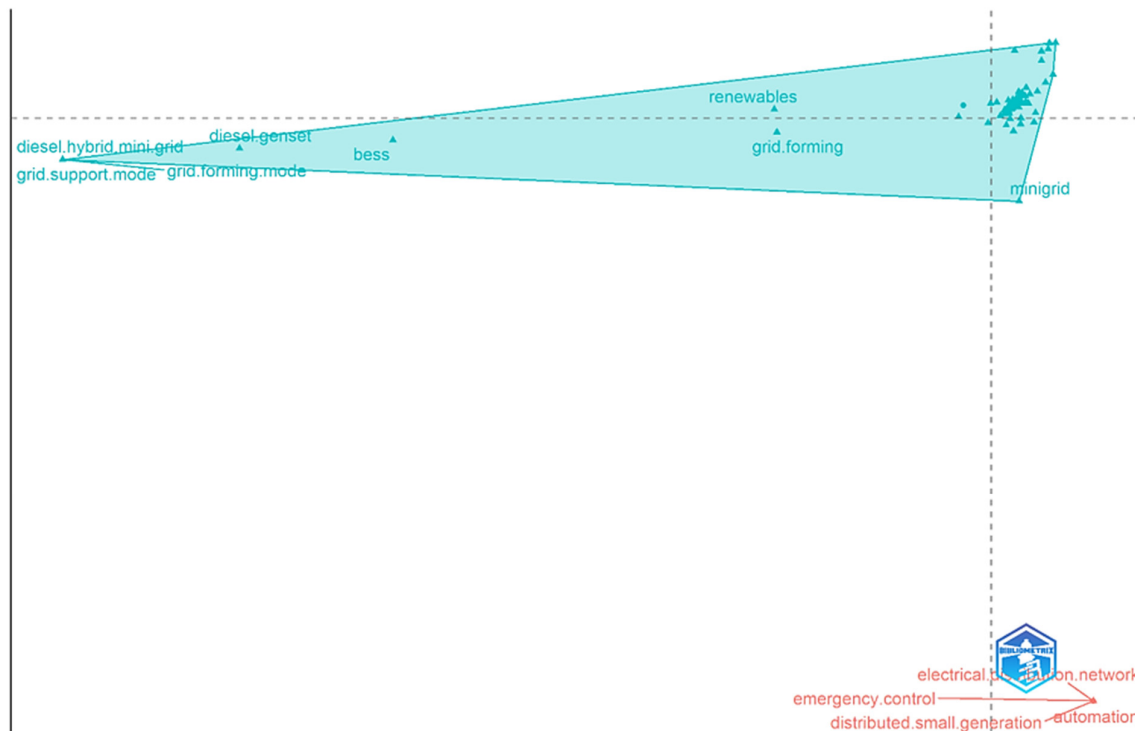


Figure 6. Factorial analysis of keywords.

The intermediate positioning of terms like “grid forming” along the vertical axis suggests transitional concepts that bridge generation and distribution concerns, as grid-forming capabilities are essential for both renewable integration and network stability. The factorial analysis thus shows that while renewable-hybrid generation dominates research attention, critical gaps persist in addressing the integrated optimisation of generation, storage, and distribution network operation. This finding underlines the need for multidisciplinary research frameworks that simultaneously consider generation diversity, energy storage coordination, distribution network constraints, and automated control strategies to develop holistic solutions for the technical and operational challenges confronting low-voltage mini-grid deployment in resource-constrained environments.

4. Thematic Synthesis of Technical Challenges of Mini-Grids

This section presents a synthesis of the papers that qualified for the systematic review on the technical challenges of mini-grids. The reviewed studies are systematically grouped into key thematic areas to provide a comprehensive understanding of the current state of research, highlight major advancements, and identify existing knowledge gaps. The thematic areas include: (1) power quality, stability, and frequency regulation challenges in mini-grids; (2) energy storage integration, battery management, and system reliability in mini-grids; (3) control system architecture, coordination, and automation challenges; (4) renewable energy integration, variability management, and curtailment; and (5) system design, planning, and techno-economic optimisation. Each of the following sub-sections discusses these thematic areas in detail, outlining the core technical issues addressed in the literature and revealing critical areas that require further investigation to enhance the performance, resilience, and scalability of mini-grid systems.

4.1. Power Quality, Stability, and Frequency Regulation Challenges in Mini-Grids

Power quality management is one of the most persistent technical challenges confronting mini-grid operations, manifesting through voltage fluctuations, frequency deviations, and harmonic distortions that compromise system reliability and equipment longevity. Additionally, the integration of variable renewable energy sources results in voltage and frequency variations within acceptable operational ranges [87–90]. This problem becomes critical as renewable penetration levels exceed conventional thresholds. Voltage regulation challenges manifest across multiple operational contexts and geographic locations, with severe implications for system reliability and equipment longevity. For example, Nkolokosa et al. [91] reported significant voltage deviations in Kenyan mini-grids, where Hadado and Ndeda Island sites exceeded recommended thresholds of plus or minus 10%, directly compromising power quality and threatening connected equipment. These voltage variations, coupled with poor power factor measurements at Locheromoit, which registered only 0.75 compared to more acceptable values of 0.87 and 0.89 at other sites, demonstrate how inadequate voltage control cascades into broader system performance degradation. The study by Sulaeman et al. [92] reinforced these concerns by emphasising that voltage measurements constitute the minimum requirement for implementing proper power quality assessments. Yet, many mini-grids lack even this basic monitoring capability. Ayoubi et al. [93] addressed these voltage challenges through advanced control strategies, proposing model predictive control for three-phase four-leg inverters that simultaneously compensate for unbalanced load conditions and minimise neutral-to-ground voltage. However, the complexity of such solutions may limit their applicability in resource-constrained settings.

Frequency instability is another equally critical challenge in diesel-hybrid systems operating with high renewable penetration, where rapid power fluctuations from intermittent sources create operational difficulties. In view of this, Wies et al. [94] investigated frequency regulation in wind-diesel mini-grids. They found that system instability stems from multiple compounding factors, including highly variable wind generation, unbalanced single-phase loads distributed across multiple branches, large instantaneous load changes, reactive power overcompensation, and critically, lower machine inertias that provide insufficient damping. The authors' genetic algorithm-based proportional integral derivative diesel speed controller demonstrated improved frequency regulation compared to standard controls, suggesting that advanced control strategies can mitigate, but not eliminate, these fundamental challenges. Mipoung et al. [95] explored alternative approaches by examining how fixed-pitch type-one wind turbines might assist with frequency support in storage-less diesel hybrid mini-grids. The study found that increased droop slopes in these inexpensive turbines could reduce both frequency variations and power demand fluctuations from diesel generators. Chaudhary et al. [96] extended this analysis to minigrid clusters in Ethiopia, demonstrating that interconnecting multiple minigrids facilitates the sharing of generation and battery energy storage systems, thereby improving frequency stability across the broader network.

Similarly, harmonic distortion and power quality degradation are additional layers of complexity in systems with power electronics interfaces and nonlinear loads. Tan et al. [97] developed a distribution static compensator using a compensatory fuzzy neural network with an asymmetric membership function controller to address total harmonic distortion and power factor issues in mini-grids serving nonlinear and linear inductive loads. Their work highlighted how traditional proportional-integral controllers prove inadequate for managing DC-link voltage regulation under variable load conditions, necessitating more sophisticated control approaches. However, Nkolokosa et al. [91] found that harmonic distortions and frequency deviations in their studied Kenyan minigrids had no significant negative impact on quality and stability performance, suggesting that the effects

of harmonics may be context-dependent and require site-specific evaluation rather than universal mitigation strategies. The challenge of maintaining power quality extends beyond steady-state operation to include transient events and system disturbances that can trigger cascading failures. Menniti et al. [98] investigated virtual synchronous generator strategies based on grid-forming inverters that emulate synchronous generator behaviour to ensure frequency and voltage stability within minigrids. Through simulation, they demonstrated that such approaches maintain stability during sudden load variations. Similarly, Nguimfack-Ndongmo et al. [99] introduced an adaptive nonlinear control strategy for virtual synchronous generators in solar PV systems, specifically targeting stability improvements during major disturbances, power fluctuations, and transitions between standalone and grid-connected modes. These advanced control strategies require computational resources and technical expertise that may not be available in many mini-grid deployment contexts.

Likewise, unbalanced loading conditions can pose significant challenges for three-phase mini-grid systems, particularly those serving single-phase loads in rural electrification scenarios. Ninad and Lopes [100] proposed per-phase vector control strategies for four-leg grid-forming inverters to provide balanced voltages despite highly unbalanced loads, noting that such systems must cope with supplying active power in one phase and absorbing it in another due to the presence of a single-phase renewable energy source. Ayoubi et al. [93] reinforced these findings, demonstrating that unbalanced load compensation requires multi-objective control functions that simultaneously track voltage references and minimise neutral-to-ground voltage. These complexities illustrate that load imbalance is not simply a power quality issue, but a fundamental design consideration that necessitates the integrated co-design of generation, distribution, and control systems.

4.2. Energy Storage Integration, Battery Management, and System Reliability in Mini-Grids

This thematic area highlights studies that address the integration of energy storage, battery management, and system reliability in mini-grids. Energy storage systems are crucial components for ensuring the reliability and performance of mini-grids. However, their integration introduces technical challenges, including capacity sizing, charge–discharge management, battery degradation, and coordination of the control system. The dual role of storage systems in providing both short-term power quality support and longer-term energy shifting creates conflicting operational requirements that remain inadequately addressed in many implementations. Recent studies have demonstrated that robust low-carbon operation can be enhanced through the integration of virtual energy storage within coordinated control frameworks [101]. For the case of battery capacity sizing and degradation management, Kaluwa and Bekker [102] analysed the Tsumkwe mini-grid in Namibia. They identified that weak batteries exacerbated excessive diesel consumption because generators simultaneously powered the system and charged degraded batteries, with insufficient solar PV charging during daylight hours exacerbating the problem. The authors concluded that undersized or degraded battery storage forces increased reliance on diesel generation, undermining both economic performance and environmental objectives. Osei et al. [103] investigated hydrogen production from redundant solar energy in Ghanaian mini-grids as an alternative long-duration storage solution. It was observed that, although lithium-ion batteries provided a lower levelized cost of storage at \$0.218/kWh, hydrogen-fuel cell pathways achieved a higher cost at \$0.249/kWh. This is because lithium-ion batteries have lower costs due to higher efficiency, technological maturity, and lower capital and conversion losses. In contrast, hydrogen systems incur additional costs from electrolysis, storage, and fuel-cell conversion. However, hydrogen-fuel cell provide seasonal and multi-day storage capabilities that batteries cannot match.

Likewise, battery management systems and control strategies are complex due to state-of-charge monitoring, charge–discharge coordination, and protection against abuse conditions (ref). Singh and Lopes [104] developed a battery energy storage system that operates in multiple modes, balancing loads, maintaining a unity power factor for generators, and forcing generators to operate within desired power ranges during genset support mode. Additionally, it provides balanced voltage to unbalanced loads during grid-forming mode. However, the laboratory implementation revealed practical challenges in achieving these multiple simultaneous objectives under rapidly changing conditions. Kliche et al. [105] addressed uncertainty in battery operation through chance constraint formulation in their optimal control problem for mini-grids, recognising that probabilistic approaches better capture the stochastic nature of renewable generation, demand, and ambient temperature effects on battery performance. Nonetheless, the theoretical framework requires validation under real-world operating conditions, where uncertainty sources interact in complex and often unpredictable ways.

Kebir et al. [106] explored the use of second-life batteries for school electrification in Kenya. The authors reported that such systems decreased the levelized cost of electricity by 5.6% to 35.3% in 97.2% of scenarios compared to new batteries, with payback periods reduced by 8.2% to 42.9%. However, the analysis acknowledged that variability in second-life battery condition, capacity fade rates, and remaining useful life creates uncertainty in system performance that requires monitoring and management capabilities. The technical challenge lies not only in identifying suitable second-life batteries but also in developing robust testing protocols, performance prediction models, and adaptive control strategies that can accommodate the inherently heterogeneous characteristics of repurposed battery banks.

Similarly, other studies have revealed that battery-to-grid and vehicle-to-grid integration introduces additional layers of complexity regarding bidirectional power flow control, communication protocols, and coordinated charging strategies. Saini et al. [107] investigated cloud energy storage in conjunction with electric mobility in residential mini-grids. The findings indicate that scenarios involving electric scooters generated 18.72% higher revenue in summer and 29.71% higher revenue in winter compared to systems without mobility integration. However, the analysis discovered that achieving these benefits requires coordination between distributed battery resources, real-time state-of-charge monitoring across multiple users, and dynamic pricing mechanisms that incentivise beneficial charging behaviours. Rosner and Lienkamp [108] proposed modular battery systems for enhanced integration between electric mobility and rural electrification, suggesting that hybrid vehicle battery systems could support electrification of heavier vehicles in minigrids and provide grid services. However, the practical implementation of such concepts faces barriers, including the standardisation of battery interfaces, the development of appropriate communication protocols, and the establishment of regulatory frameworks governing distributed storage participation in mini-grid operations.

Furthermore, the literature has highlighted that energy management algorithms for storage systems must simultaneously optimise multiple conflicting objectives, including cost minimisation, reliability maximisation, battery lifetime extension, and power quality maintenance. Messaoud et al. [109] proposed a fuzzy logic-based energy management system for isolated mini-grids with multiple energy sources; however, their simulation-based validation did not address how the fuzzy membership functions and rule bases should adapt to changing system conditions over time. Nanda et al. [76] developed an intelligent energy management system for microgrids with energy storage integration that continuously monitors demand and supply to determine optimal combinations of renewable generation and stored energy. However, their approach relies on pattern recogni-

tion, which may fail under novel operating conditions not represented in the training data. The fundamental challenge lies in developing energy management strategies that remain robust across the different operating conditions, load patterns, and component degradation trajectories encountered over multi-decade system lifetimes.

4.3. Control System Architecture, Coordination, and Automation Challenges

Control system design and coordination are foundational technical challenges that determine whether mini-grids can successfully integrate multiple generation sources, maintain stability under varying conditions, and respond appropriately to disturbances. The transition from simple single-source systems to complex hybrid configurations necessitates hierarchical control frameworks; however, implementation complexity often exceeds the available technical capacity in deployment locations. Hierarchical control architectures provide a framework for coordinating multiple system functions across different timescales; however, their implementation introduces complexity in terms of communication requirements, computational burden, and coordination algorithms. Abdelghany et al. [110] developed a hierarchical model predictive control scheme for wind-hydrogen microgrids that separates long-term operations, managed by high-level control considering day-ahead forecasts and market participation, from short-term operations, handled by low-level control, which compensates for forecast deviations and addresses real-time dynamics. Their approach, implemented through mixed-integer linear programming, achieved coordinated operation but required substantial computational resources and sophisticated forecasting capabilities. Juma and Ayeng'o [75] investigated energy management systems in Malawian mini-grids. The authors found that while such systems reduce downtime and improve operational reliability, adoption remains constrained by high capital expenditure, limited technical expertise, and resource constraints. This disparity between theoretical control capabilities and practical implementation capacity indicates a fundamental barrier to achieving optimal mini-grid performance in many deployment contexts.

In the work of Boyko et al. [111], the authors advocated for intelligent automatic control systems governed by decentralised algorithms that provide coordinated operation of emergency control and power flow automation in community mini-grids. The authors argued that such approaches enhance reliability by eliminating single points of failure. Conversely, Palacios-Bocanegra and Molina [112] implemented centralised control using optimal power flow solutions within supervisory control and data acquisition systems for minigrid power management, demonstrating benefits in terms of system-wide optimisation. Rodriguez-Bernuz and Junyent-Ferré [113] proposed a hybrid approach combining decentralised droop controllers for local stability with centralised optimal power flow for setpoint adjustment. It was observed that the architecture achieves both rapid response and optimal steady-state operation. The choice between these alternatives depends on the reliability of the communication infrastructure, the availability of computational resources, and specific operational priorities that vary across deployment contexts.

Other studies in the literature show that synchronisation and grid interconnection control are challenging technical requirements, especially when connecting multiple autonomous mini-grids or interfacing with unreliable utility grids. In this context, Degefa et al. [114] highlighted that existing protocols often prove inadequate for the specific characteristics of mini-grid systems. Juliana et al. [115] reported that a unified power flow controller for two interconnected solar mini-grids can regulate power flow on interconnection lines, maintaining voltage stability and provide reactive power compensation. However, the study revealed that successful implementation requires precise control of active and reactive power, protection coordination, and careful tuning of controller parameters. Adhikary et al. [116,117] developed automatic synchronisers for connecting induction

motors as generators in mini-grid systems, proposing low-cost electronic circuitry using exclusively OR gates, relays, and contactors to achieve a soft connection between generators only after synchronisation. Although such simplified approaches enhance accessibility, they sacrifice the advanced functionality and precise control available in more sophisticated synchronisation systems.

In other studies, model predictive control strategies offer theoretically optimal performance but encounter practical implementation barriers related to computational requirements, model accuracy, and parameter sensitivity. Kliche et al. [105] formulated probabilistic optimal control problems for mini-grids using joint chance constraints to address uncertainties in renewable generation, demand, and ambient temperature. However, they acknowledged that their approach requires accurate probabilistic models of uncertainty, which may be difficult to obtain in practice. Abdelghany et al. [110] developed mixed-logic dynamic frameworks for wind-hydrogen systems that consider various logic states and corresponding continuous dynamics, resulting in mixed-integer linear programmes that must be solved numerically at each time step. The computational burden of these approaches raises questions about their real-time implementability on the embedded control hardware typically deployed in mini-grid systems. Ninad and Lopes [100,118] proposed per-phase vector control techniques that eliminate the need for symmetrical component decomposition, resulting in higher dynamic performance compared to conventional three-phase control approaches. The method was successful for systems with unbalanced loads and single-phase renewable generation, though it requires more complex implementation than standard control schemes. Nguimfack-Ndongmo et al. [99] improved stability during transitions and disturbances by employing an adaptive nonlinear control for virtual synchronous generators, which utilises adaptive tuning to ensure optimal responses to grid modifications and includes online estimators for virtual mechanical power. However, the complexity of these advanced control strategies raises concerns about their maintainability in locations with limited technical support infrastructure.

4.4. Renewable Energy Integration, Variability Management, and Curtailment

The integration of variable renewable energy sources into mini-grids presents challenges, including managing generation variability, maintaining system stability, and achieving optimal capacity utilisation. These challenges become critical as renewable penetration levels increase beyond modest fractions, requiring forecasting, control strategies, and operational approaches that often exceed available technical and institutional capacity. For instance, solar PV integration challenges include improving generation forecasting accuracy, managing ramp rates, and determining optimal capacity sizing in relation to load profiles and storage availability. Opoku et al. [73] reported midday generation surpluses averaging 2250 kWh/month due to mismatches between peak production and local demand, with excess energy curtailed once batteries reached full charge from Ghanaian solar mini-grids. The study machine learning models predicted redundant energy ranging from 56.98 to 119.86 kWh/day, demonstrating systematic underutilisation of installed capacity that limits socio-economic benefits and reduces system economics. This curtailment challenge demonstrates a fundamental tension between achieving high renewable energy fractions and maximising capacity factor utilisation. Tonkoski et al. [119] demonstrated that active power curtailment strategies employing frequency-power droop control for solar PV inverters in diesel-hybrid mini-grids reduced frequency variations and prevented diesel genset operation at reduced loading during periods of excess power. However, curtailment implies an economic loss that undermines the financial viability of renewable energy investments when substantial generation capacity sits idle during peak solar radiation periods.

Likewise, wind energy integration presents challenges related to turbulence-induced power fluctuations, the limited predictability of wind resources, and coordination with other generation sources across multiple time scales. Mipoung et al. [95,120] found that inexpensive turbines could provide some frequency regulation through their inherent power-frequency characteristics for fixed-pitch type-one wind turbines for frequency support in diesel-hybrid mini-grids. However, their effectiveness remained limited compared to variable-speed turbines with pitch control. Chaudhary et al. [96] designed mini-grids utilising solar PV and micro-hydro generation in Ethiopian villages. The authors highlighted that combining multiple renewable sources with different generation profiles reduces overall system variability. Nonetheless, effective renewable integration requires careful coordination of multiple generation sources, appropriately sized storage, and control systems that may challenge implementation capacity in many contexts. Hydropower variability due to seasonal and multi-year hydrological patterns presents long-term challenges that exceed the capabilities of conventional battery storage systems. Abuzayed et al. [81] examined Zambia's heavy reliance on hydropower, which makes the system vulnerable to climate-induced hydrological variability that causes severe load shedding during droughts. The system modelling indicated that, even in the absence of increased access efforts, at least 2.6 GW of solar power would be required by 2030, potentially reaching 8.4 GW under higher access scenarios or low hydropower availability.

Generation forecasting accuracy influences the efficacy of renewable energy integration strategies; however, forecast errors propagate through operational decisions and control actions in ways that can exacerbate rather than mitigate variability. Ioannou et al. [121] developed distributed artificial intelligence frameworks for power forecasting in mini-grids using temporal convolutional networks, claiming accurate hour-ahead predictions based on data from the previous day. However, the validation focused on normal operating conditions without examining forecast performance during unusual weather patterns, equipment failures, or other off-nominal situations when accurate forecasting becomes most critical. The gap between forecast accuracy under favourable conditions and performance during challenging circumstances remains inadequately characterised in mini-grid contexts. Pelland et al. [122] documented that the Nemiah Valley PV-diesel mini-grid would deliver approximately 10% more energy annually if all output could be absorbed rather than curtailed when generation exceeded load. This curtailment, which occurs when PV penetration reaches 36% of peak load, suggests that increasing renewable fractions beyond modest levels requires alternative approaches, such as demand-side management, additional storage capacity, or productive use applications that can absorb excess generation. Load-generation matching optimisation is another technique for reducing curtailment and improving renewable utilisation through demand-side interventions and flexible loads. In this context, Keddar et al. [11,74] investigated the integration of electric cooking on hybrid solar PV-diesel mini-grids. They found that the coordinated management of cooking loads could improve renewable utilisation and introduce new challenges regarding network constraints and generation capacity requirements. The study of a smart battery charging system for electric cooking devices demonstrated that regulating charging rates based on system conditions can mitigate network impacts and enhance grid accommodation capacity. However, implementing such demand-side strategies requires advanced metering infrastructure, communication systems, and customer engagement mechanisms that may prove difficult to establish and maintain in many rural contexts.

4.5. System Design, Planning, and Techno-Economic Optimisation

Mini-grid system design and planning can encounter technical challenges. Gambino et al. [123] emphasised that energy need assessment provides critical inputs for business

modelling and mini-grid design, with assessment accuracy directly affecting technical and financial feasibility. The authors advocated for inclusive methodologies adaptable to different community contexts, prioritising data collection methods capable of achieving representative samples with high accuracy in estimating electricity substitute consumption. Scott and Coley [124] concluded that load profiles reflect complex interactions among appliance ownership, occupancy patterns, and socio-economic status, rather than simple, predictable relationships, in Tanzanian mini-grids. Herraiz-Cañete et al. [125] compared deterministic and stochastic demand forecasting approaches for isolated rural communities, concluding that deterministic methods require less information and processing. In contrast, stochastic approaches yield more realistic results, which are crucial for effective mini-grid design. This tension between data requirements and forecast accuracy creates challenges for project developers operating under resource and time constraints.

Likewise, system sizing optimisation must balance multiple competing objectives, including minimising lifecycle costs, achieving target reliability levels, maximising renewable energy fractions, and ensuring adequate capacity for future load growth. Sawadogo et al. [86] employed particle swarm optimisation to minimise LCOE and adhere to reliability constraints for a Burkina Faso solar mini-grid. It was observed that optimisation-based approaches can identify cost-effective configurations. However, the authors acknowledged that optimal sizing depends critically on the assumed load profiles, component costs, and operational constraints, which contain substantial uncertainty. In the work of Agbo et al. [42], the authors utilised the MicroGridsPy optimisation model to examine different demand scenarios and system configurations for Nigerian rural electrification. Hybrid systems with solar PV, battery storage, and backup generators, incorporating capacity expansion over time, proved to be the most cost-effective. The system-optimised scenario achieved 94.7% renewable energy penetration, with generators contributing less than 6% of the supply. However, reaching this performance required optimisation and careful capacity planning, which may challenge many implementers.

Similarly, other studies have highlighted that technology selection decisions involve evaluating alternative generation, storage, and distribution technologies across technical performance, economic cost, environmental impact, and local appropriateness dimensions. For example, Al-Bayati et al. [49] documented that systems combining solar PV, wind turbines, diesel generators, battery storage, and converters achieved an optimal balance of cost, environmental impact, and reliability. The optimal configuration required 666 kW of photovoltaic power, 47 wind turbines, generators totalling 2600 kW, 864 kWh of battery storage, and 699 kW of converters, achieving a levelized cost of \$0.123/kWh. However, the study's optimisation approach and detailed component specification may exceed the planning capacity available to many developers. Habib [126] conducted load flow studies using OpenDSS software for mini-grids serving agricultural irrigation. The results show that voltage drops from the grid to transmission line endpoints remained within 10% limits at maximum load for centralised configurations, with line losses of only 1.22%. The analysis indicated that distributing generation at multiple locations provided minimal improvement over a centralised architecture, validating the efficiency of their main distribution system design. Chikumbanje et al. [127] introduced a loading index as a rule of thumb for pre-assessing whether detailed grid integration studies are needed when connecting mini-grids, arguing that such simplified screening tools can help prioritise engineering resources. However, these distribution planning approaches assume relatively predictable load distributions and generation locations that may not reflect the organic growth patterns of many mini-grids.

In the case of techno-economic optimisation, Mbouteu Megaptche et al. [128] employed a multi-objective genetic algorithm and cuckoo search optimisation for Cameroonian hybrid

renewable energy systems, examining PV-wind-battery and photovoltaic-wind-hydrogen-fuel cell configurations across techno-economic and social dimensions. The authors found that PV-wind-battery-hydrogen configurations optimised by genetic algorithms achieved 72.91% system efficiency, with a 0.4457 loss of power supply probability. However, hydrogen components proved cost-prohibitive due to inefficiencies in the electrolyser and fuel cell. Dagnachew et al. [129] modelled Sub-Saharan African electricity access pathways, projecting that baseline developments would not achieve universal access and that central grid extension must be complemented with off-grid systems. The results indicated that for low consumption levels, off-grid technologies constitute the most important access-increasing technologies, while for high consumption, grid extension proves more economical. Ouédraogo [130] revealed that achieving universal access by 2035 would require \$7.8 to \$10.44 billion, with mini-grid photovoltaic systems playing a significant role. However, these planning models rely on assumptions about technology costs, demand evolution, and policy environments that introduce substantial uncertainty into resulting recommendations.

5. Summary of Thematic Insights and Future Research Directions

Low-voltage mini-grids face several technical challenges and operational constraints that limit their ability to provide reliable and sustainable electricity access to remote communities, as shown in Table 1. For example, the intermittency and uncertainty of renewable energy sources pose operational challenges, necessitating the use of batteries for energy storage to mitigate instability. However, optimising the lifespan of battery energy storage systems requires balancing degradation against operational expenses [105]. In addition, power quality degradation is another critical technical limitation, as existing standards are often impractical in energy access contexts, necessitating pragmatic approaches such as the Multi-Tier Framework and Quality Assurance Framework. These frameworks require at least voltage measurements for proper implementation, which is challenging due to resource constraints in remote areas [92]. Voltage variations, low power factors, and harmonic distortion are primarily driven by the characteristics of specific loads connected to the system. Field studies indicate that load composition can result in an average power factor as low as 0.75, compared with acceptable ranges of 0.87–0.89, thereby affecting overall power quality and system stability. Additionally, voltage deviations from recommended values are observed, with ranges of 10% to −15% and $\pm 10\%$ [91]. Moreover, system protection remains inadequately addressed, as the adequate protection of LVDC microgrids remains a challenge hindering their adoption, with conventional protection schemes struggling to handle both low-impedance and high-impedance faults in these networks [131].

Similarly, technical design inadequacies are evident, with over-dimensioned mini-grids resulting from initial load overestimation and grant influence, leading to altered operating decisions that exacerbate capacity constraints and worsen battery degradation [132]. The inability to recover even operations and maintenance costs at current consumption levels due to considerably higher electricity supply costs than applied tariffs emphasises the economic unsustainability created by poor design [132]. Load forecasting is another particular challenge, as target communities differ in terms of needs and contextual conditions, requiring inclusive methodologies that are adaptable on a case-by-case basis. However, the scarcity of resources for development aid requires very tight designs that minimise investment and operational costs, demanding accurate energy need assessments that directly affect technical and financial feasibility [123,125]. The complexity increases with demand patterns, as load profiles are determined by a complex mix of appliance ownership, occupancy, and socio-economic status, making prediction difficult without comprehensive data [124]. It is observed that the integration of electric cooking appliances introduces severe constraints, with voltage drop, voltage unbalances, and capacity short-

ages emerging as critical technical risks. Generation capacity requirements, rather than network constraints, limit the penetration of electric cooking in mini-grids [11].

Table 1. Summary of reported technical challenges, barriers, and operational constraints in low-voltage mini-grids.

Technical Barrier/Constraint	Mode of Application/Purpose	System Description	Ref.
Voltage fluctuation, frequency deviation, harmonic distortion, and poor power factor	Power quality analysis in Kenyan mini-grids	PV-based low-voltage mini-grids	[91]
Difficulty in monitoring power quality (voltage and harmonics) due to resource constraints	Power quality monitoring in remote mini-grids	Microgrid/mini-grid power quality systems	[92]
Frequency instability due to variable renewable generation	Frequency regulation and stability in hybrid systems	PV–wind–diesel hybrid mini-grids	[133]
Voltage imbalance and capacity shortage from e-cooking integration	Electric cooking load accommodation	Hybrid PV/diesel mini-grid	[11]
Degraded batteries and capacity constraints from load overestimation	Mini-grid design and operation	PV mini-grids in Ghana	[132]
Limited technical know-how and a lack of qualified technicians	Solar mini-grid deployment in island communities	Solar PV mini-grids	[134]
Battery degradation and uncertainty in renewable energy/demand	Reliable operation under uncertainty	Standalone mini-grids with BESS	[105]
Voltage drop constraints, inaccurate load forecasting	Grid integration and expansion planning	Multi-feeder LV mini-grids	[127]
Poor system sizing, low reliability of the power supply	Technical sustainability analysis	PV mini-grids (Mozambique, Ghana)	[132,135]
Sizing, system utilisation, O&M deficiencies, inadequate training	Operational performance analysis	15–19 kWp PV mini-grids	[136]
Frequency deviations from solar intermittency	PV integration in diesel-dominated mini-grids	PV–diesel hybrid mini-grids	[119]
Frequency instability due to fluctuating wind	Wind integration in diesel hybrids	Type-1 and Type-2 WT–diesel mini-grids	[95,120]
SOC management and prolonged emergency supply during disasters	Islanded operation for disaster resilience	PV–battery microgrids	[137]
Neutral-to-ground voltage and unbalanced loads	Voltage unbalance compensation	Islanded mini-grids with a four-leg inverter	[93]
Suboptimal control settings affecting battery and PV output	Model validation for operational optimisation	PV mini-grids in Kenya (RESILIENT project)	[138]
Redundant energy generation due to demand mismatch	Energy use optimisation for cooking	30.6 kW PV mini-grid	[73]
Coordination of hybrid sources and SOC control	Power flow management among multiple sources	Hybrid PV/diesel/battery mini-grids	[109]
Complex load dynamics under uncertain renewable inputs	Distributed nonlinear collaborative control	PV energy storage mini-grids	[139]
Limited reactive power compensation causes poor voltage regulation	Power quality deterioration in LV mini-grids	PV-hybrid LV mini-grids in Kenya	[91]

Likewise, control system limitations constrain mini-grid performance and stability, as most existing mini-grids in developing countries lack control strategies that optimise energy use and guarantee consistent performance, with specific gaps in data availability, communication infrastructure limitations, and social and technical constraints [75]. The need for user-friendly control solutions designed to the specific needs of isolated communities remains largely unmet [75]. Grid integration is also another unique challenge, as the interconnection of mini-grids emerges as a strategic approach to enhance reliability, efficiency, and resilience. However, managing power flow, voltage stability, and reactive power compensation during solar energy variability requires complex control [115]. Therefore, virtual synchronous generator control using simplified third-order models is a viable potential solution for improving stability during sudden changes, major disturbances, power fluctuations, and mode switching between standalone and grid-connected operations; yet, implementation complexity remains high [99]. Frequency stability is also problematic, as fluctuating wind energy requires additional power from diesel generators. Grid frequency varies more, resulting in increased unit cycling and leading to power quality and maintenance issues. Large variations in wind power and load demand also increase the rate of change in frequency and frequency excursions, leading to load shedding and the tripping of renewable energy generators [120].

In addition, the integration and management of energy storage systems are also critical technical and economic barriers. Redundant energy generation during peak sunshine hours, when battery energy storage is full, leads to low profitability for mini-grid systems. Mismatches between PV energy generation and household energy demand create redundant energy during afternoon periods [73]. A hydrogen storage alternative has been proposed for harnessing redundant energy from solar mini-grids [140–142]. However, although hydrogen storage is technically feasible, its levelized cost is about 13% higher than that of lithium-ion storage [103]. In mini-grids, battery degradation aggravates operational challenges, with excessive diesel use stemming from generators' dual role in powering systems and charging weak batteries, which is further exacerbated by demand and insufficient PV charging during daylight hours [102]. Significant disparities in capital expenditure per kW among operators, with larger systems achieving better economies of scale through advanced energy management system functionalities, create barriers to smaller-scale deployment [75]. Thus, the high capital expenditure, combined with technical expertise and resource constraints, fundamentally limits operational efficiency improvements in the adoption of energy management systems [75].

It is worth mentioning that socio-economic and institutional barriers interact with technical limitations to constrain sustainability, as financial constraints, complex implementation strategies, and limited monitoring mechanisms render energy policies ineffective in promoting mini-grid development [143]. Nearly 600 million people in Sub-Saharan Africa still lack access to reliable electricity services [144]. Nevertheless, remote areas are considered too poor to afford cost-reflective tariffs, with more clarity needed between the enthusiasm expressed regarding mini-grid potential and the level and quality of finance available [19]. Although hybrid ownership, partially subsidised models, focusing on anchor customers, and bundling projects into financial portfolios are the most promising business strategies, there is no one-size-fits-all solution, and optimistic narratives about private sector participation may not translate into greater accessibility and affordability for geographically remote and low-income users [19]. The lack of proven guidelines from project developers, despite the scarcity of resources requiring very tight designs, perpetuates suboptimal implementations [123]. Community engagement challenges are exacerbated by socio-technical barriers, including land disputes and illegal connections on the social side, as well as limited technical expertise and a lack of qualified technicians on the technical

side. This requires the involvement of local communities, training, and the transfer of technical expertise, as well as increased power generation capacity [134].

According to [14], performance monitoring and reliability assessment remain inadequately addressed across implementations, as solar power conversion efficiency was generally low with a 25–45% performance ratio due to inefficiencies in battery bank, distribution losses, and unused losses, with overall system efficiency ranging from 4 to 7%, consistent with the literature reporting PV power systems in tropical climates with an efficiency of 5–15%. These low efficiencies emphasise the importance of system maintenance, load management, and considering the impact of climate change on the reliability and sustainability of mini-grids. However, operators and technical skill deficiencies impact performance issues, with operational and commercial success achievable through optimal system design and utilisation, effective operation and maintenance, and addressing technical, commercial, and social issues [136]. Despite off-grid systems facing the risk of grid encroachment, connecting with the central grid may be possible at some point in the project lifetime, requiring multiple analysis use cases for power system planners and operators to include off-grid systems in planning and operational time frames [145].

Furthermore, hardware and component-level limitations create additional operational constraints, as asynchronous interconnection of large grids transforms power systems from large grids operating synchronously to small grids operating independently, enhancing sensitivity to grid frequency deviation perturbations, with serious deviation of grid parameters leading to power accidents, and even small-scale frequency fluctuations posing threats to automatic generation control [139]. The lack of effective fault detection and location algorithms for LVDC microgrid interconnections, which require high-sampling-rate sensors, implementation, and high communication bandwidth, creates protection gaps [131]. Distribution network design presents challenges, as voltage drop and voltage imbalance issues can be reasonably addressed by using cables with larger cross-sectional areas; however, generation capacity requirements remain the primary barrier [11]. The technological diversity creates compatibility issues, with a hybrid minigrid two-area system comprising solar PV systems, wind turbines, diesel generators, and energy storage systems requiring intelligent, fine-tuned, and optimised controllers to reduce deviations in frequency and tie-line power signals [133].

It is worth noting that critical areas requiring future research are evident in the above limitations. First, the development of cost-effective remote monitoring tools as a mandatory requirement of mini-grid design, essential for power quality assessments and enabling assessments for transients and harmonics, remains urgent, mainly solutions addressing challenges associated with mini-grid control in developing countries, including data availability, communication infrastructure limitations, and social and technical constraints [75,92]. Second, advanced energy storage integration strategies beyond conventional batteries warrant investigation, as hydrogen storage can complement batteries, provide seasonal and multi-day storage capabilities, and reduce renewable curtailment. Wider adoption is supported by cost reductions, efficiency improvements, and enabling policies. Third, adaptive nonlinear control strategies utilising online estimators for virtual mechanical power and specific time constants, which enable real-time adjustments, require further development for diverse mini-grid configurations [99]. Fourth, comprehensive frameworks for techno-economic analysis, which compare business models for typical off-grid systems and planned off-grid systems for grid arrival, explore mini-grid interconnection methods, and assess their impact on grid stability, require refinement [145]. Fifth, investigating factors that contribute to oversized plants, including initial load overestimation and grant influence, along with analysing efficiently designed tariffs and applying tariff regulations to improve financial performance, requires a systematic study [132]. Finally, the development of methodologies

providing effective applied solutions to the lack of proven guidelines, giving priority to data collection methods able to achieve large representative samples with high accuracy in estimating energy consumption from electricity substitutes, deserves attention [123]

6. Conclusions and Way Forward

This study assessed the technical challenges and operational constraints that have affected low-voltage mini-grids over the past two decades (2005–2025). Evidence from 92 systematically reviewed studies highlights that, although mini-grids are a sustainable solution for rural electrification, persistent engineering and operational inefficiencies continue to undermine their reliability and sustainability. The major technical issues identified include power quality degradation, frequency instability, inadequate control and automation systems, poor energy storage integration, and suboptimal system design and planning. Power quality problems stemming from voltage fluctuations, harmonic distortion, and frequency deviation remain among the most recurrent challenges. Field studies in African and Asian contexts show that voltage deviations of ± 10 – 15% and poor power factors (as low as 0.75) compromise equipment lifespan and consumer satisfaction. These problems are worsened by inadequate monitoring and control capabilities in most rural mini-grids, where the absence of voltage and harmonic measurement infrastructure limits the ability to enforce power quality standards. Frequency instability in hybrid systems with high renewable penetration emanates from the low inertia of renewable sources and the absence of advanced control mechanisms. Although model predictive control and virtual synchronous generator technologies are viable potential solutions, their complexity and high computational requirements make them difficult to implement in resource-limited environments.

Additionally, energy storage integration is a critical operational bottleneck. Battery degradation, improper sizing, and weak charge–discharge coordination contribute to energy losses and reduced reliability. In several cases, degraded battery banks have led to over-reliance on diesel backup systems, eroding the economic and environmental benefits of renewable-based mini-grids. Although hydrogen-based and hybrid storage configurations are viable options for addressing long-term energy balancing, their adoption remains constrained by high costs and limited technical expertise. Furthermore, energy management systems, essential for optimising the interaction between generation, storage, and load, are seldom applied effectively due to capital constraints and a lack of skilled personnel.

Similarly, control system architecture and automation challenges remain pervasive. Mini-grids typically operate using rudimentary control setups that are unable to coordinate multiple generation sources, respond to real-time disturbances, or optimise load dispatch. Hierarchical and decentralised control frameworks, although well-established in theory, are rarely implemented in practice due to computational complexity and limitations in communication infrastructure. Correspondingly, synchronisation and protection coordination when interconnecting multiple mini-grids or linking them with national grids present new technical hurdles that require sophisticated automation and protection logic. Renewable energy integration introduces its own set of challenges, particularly in balancing supply variability with fluctuating demand in rural areas. Studies indicate that solar PV mini-grids often experience substantial curtailment of generation, with 10–15% of potential energy production wasted during midday hours due to limited load demand and full battery capacity. This redundancy reduces financial returns and system utilisation. Solutions such as electric cooking, water pumping, and productive-use integration have been proposed to absorb surplus energy, yet these interventions require careful load management and robust network design. Wind and hydropower integration similarly demand advanced forecasting and storage coordination, which are not yet standard practice in mini-grid design.

System design and techno-economic optimisation remain critical to the sustainable operation of mini-grids. Many systems are either over-dimensioned due to donor-driven oversizing or underperforming because of poor demand forecasting and a lack of adaptive design methodologies. Deterministic load forecasting models often fail to capture the dynamic consumption behaviours in newly electrified communities, resulting in inefficiencies. Stochastic and hybrid forecasting approaches, although more accurate, often require data and computational resources that are scarce in developing regions. Consequently, several mini-grids fail to recover even their operation and maintenance costs, rendering them financially unsustainable. The geographical distribution of research also shows significant asymmetry. Developed countries, notably the UK, India, and Canada, account for most research output. On the other hand, contributions from Africa remain disproportionately low despite the continent facing the most critical electrification challenges. This imbalance emphasises structural limitations, including limited funding, weak institutional collaboration, and inadequate laboratory infrastructure. Building regional research capacity, fostering South-South partnerships, and incentivising local innovation are therefore urgent priorities.

Accordingly, addressing the identified technical and operational challenges requires a multi-strategy approach integrating technological, institutional, and policy interventions. For example, effective power quality management requires the integration of real-time monitoring tools as a standard feature in mini-grid design. In view of this, governments and funding agencies should mandate low-cost digital metering systems capable of measuring voltage, frequency, harmonics, and load profiles. Such systems will provide the data necessary for predictive maintenance, control system tuning, and regulatory compliance. In addition, simplified versions of virtual synchronous generators and adaptive control systems should be developed for areas with limited resources. Additionally, collaborations among universities, equipment manufacturers, and utilities can facilitate technology transfer and the development of modular, user-friendly control units that enhance mini-grid stability without requiring extensive technical expertise. Policies should encourage hybrid energy storage systems that combine batteries with alternative technologies, such as hydrogen or thermal storage, to address both short-term and seasonal variability. Incentives for battery recycling and repurposing of second-life electric vehicle batteries could reduce costs and promote circular economy principles. Likewise, capacity-building programmes on battery management and thermal regulation are needed to prolong storage lifespan and reduce diesel dependency. Stakeholders must invest in data-driven demand assessment frameworks that combine household surveys, appliance ownership data, and stochastic modelling to capture evolving consumption patterns. The development of simplified optimisation tools and open-source design software, designed for African and Asian contexts, can help bridge the design capacity gap among local developers.

The limited contributions from African research institutions in the global mini-grid research domain accentuate the need for targeted funding mechanisms, such as India's MNRE or the UK's UKRI. Establishing regional research hubs and an African mini-grid research consortium will enhance local innovation and contextual technical solutions. Bilateral and multilateral donors should prioritise research components in funded mini-grid projects. Linking mini-grids with local industries, electric cooking initiatives, and agricultural processing can improve load utilisation and reduce curtailment. Policy frameworks should incentivise productive-use applications by offering concessional financing, equipment subsidies, or tariff discounts for value-adding enterprises. The absence of harmonised standards remains a barrier to scalability. Governments should adopt or adapt IEC and IEEE microgrid standards to local contexts, incorporating guidelines for planning, performance reporting, environmental assessment, and decommissioning. Regulatory authorities

must also develop clear interconnection codes for grid-tied mini-grids to ensure safe and efficient integration. Economic viability requires aligning tariffs with cost recovery and safeguarding affordability for low-income users through smart subsidies. Policymakers should explore results-based financing, blended finance, and community ownership models that strike a balance between investor confidence and social equity. Integrating mini-grids into national electrification strategies will ensure policy coherence and long-term support.

Future mini-grids must be designed with climate resilience in mind, factoring in temperature, humidity, and extreme weather events that affect component performance. Incorporating resilient technologies such as elevated solar structures, weatherproof storage units, and adaptive cooling systems can enhance reliability and lifespan under changing climatic conditions. Sustainable mini-grid deployment depends on continuous training and capacity development for technicians, operators, and community stakeholders. National energy agencies and universities should establish certification programmes and vocational training centres focused on mini-grid design, control, and maintenance. Table 2 provides a structured summary that links the research questions to their corresponding key findings, identifies knowledge gaps, and proposes future research directions. It is worth noting that the transition toward universal, sustainable energy access will depend on the ability of mini-grids to overcome technical and operational inefficiencies through innovation, collaboration, and evidence-based policy support. This review provides an empirical foundation for aligning research, investment, and regulatory frameworks to achieve resilient, inclusive, and low-carbon energy systems in the Global South.

Table 2. Summary of research questions linked to key findings, gaps, and future directions.

Research Question	Key Findings	Identified Gaps	Proposed Future Research Directions
RQ1: How has research on low-voltage mini-grids evolved over time and across countries?	Research output increased sharply after 2020, driven by initiatives related to SDG 7 and global decarbonisation efforts. The UK, India, and Canada lead contributions; African nations are underrepresented.	Weak research capacity and funding in Africa, as well as limited collaboration networks.	Develop South-South research collaborations and regional research funds; enhance African institutional participation.
RQ2: Who are the key contributors and collaboration networks?	High collaboration among developed countries; limited inter-African partnerships.	Weak institutional networks in developing regions.	Establish African mini-grid research consortia and exchange programmes.
RQ3: What are the dominant and emerging technical themes?	Themes evolved from “power quality” and “smart grids” to “renewable integration” and “energy management.”	Fragmented focus between generation and distribution system studies.	Foster holistic modelling integrating generation, storage, and network operation.
RQ4: What major technical and operational challenges are reported?	Persistent issues include voltage instability, harmonic distortion, storage degradation, and inadequate control systems.	Lack of empirical performance data; limited monitoring systems.	Develop low-cost, remote monitoring and diagnostic systems designed for rural mini-grids.
RQ5: What research gaps and future directions emerge?	Gaps in adaptive control, hybrid storage design, and context-specific techno-economic models.	Insufficient field validation and standardisation.	Advance adaptive nonlinear control, hybrid energy storage optimisation, and standardised testing protocols.

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