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Systematic Review

The Impact of Mini-Grids on Rural Energy-Access Indicators in Developing Countries: A Systematic Review

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Abstract

Mini-grids are increasingly deployed to expand rural electrification in developing countries, yet evidence on service-quality performance remains uneven. This systematic review synthesises empirical evidence from 22 peer-reviewed studies (2005–2025) on rural mini-grid performance across six energy-access indicators: electrification rate, availability of supply, hours of supply, affordability, reliability, and consistency (power quality). Using PRISMA-guided database searches in Scopus and Web of Science, 138 records were identified; following de-duplication and screening, 22 studies met the inclusion criteria. The evidence base is concentrated in Africa and Asia, and most studies adopt mixed-methods approaches combining household- and/or enterprise-level evidence with system or operational data. Across indicators, electrification outcomes are frequently positive but reported using heterogeneous metrics, often relying on connection counts rather than population-referenced rates (10/22 studies report electrification outcomes). Service availability and hours of supply vary widely, ranging from evening-only provision (~5 h/day) to near-continuous service (24 h/day), with several studies documenting demand–capacity mismatch and load shedding (9/22 quantify availability; 12/22 quantify hours). Affordability is most frequently reported (16/22 studies), spanning substantial household cost reductions in some settings to high tariffs that constrain uptake in remote contexts. Reliability is seldom quantified using extractable outage/downtime metrics (4/22 studies). No study reports standardised voltage/frequency power-quality measures; only proxy evidence relates to consistency, leaving power quality as a major evidence gap. Mini-grids can deliver meaningful improvements in rural electricity access, but the literature remains constrained by inconsistent indicator definitions, limited standardised reliability/power-quality measurement, and short monitoring horizons. Future research and regulation should prioritise harmonised service-quality metrics and longer-term, field-based performance evaluation.

Keywords: mini-grids; rural electrification; energy access; service quality; affordability; reliability; power quality; systematic review

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1. Introduction

Access to modern, reliable, and affordable energy services is fundamental to socio-economic development, yet it remains elusive for hundreds of millions in developing countries. As of 2025, approximately 666 million people worldwide still lack access to electricity. Sub-Saharan Africa now accounts for about 85% of this global deficit (565 million people), while Central and Southern Asia have reduced their unserved population from roughly 414 million in 2010 to about 27 million [1]. Rural areas are disproportionately affected by geographic remoteness, low population density, and the prohibitive costs of grid extension [2–4]. The absence of reliable electricity access perpetuates cycles of poverty by limiting opportunities in health, education, and economic productivity [5,6].

Traditional grid extension, while successful in urban and peri-urban areas, faces significant economic and technical barriers in rural contexts. The high capital costs of transmission and distribution infrastructure, combined with low population density and limited ability to pay, result in unfavourable cost–benefit ratios for utility companies [3,7]. Rural households without electricity rely on traditional energy sources such as kerosene for lighting, wood and charcoal for cooking, and diesel generators for mechanical power, all of which are associated with high costs, indoor air pollution, and environmental degradation [8,9]. The urgency of addressing rural energy poverty is underscored by its direct linkage to United Nations Sustainable Development Goal 7 (SDG 7), which calls for universal access to affordable, reliable, sustainable, and modern energy by 2030 [10].

1.1. Definition and Importance of Energy Access Indicators

The conceptualisation of energy access has evolved from a binary measure of grid connectivity to a multidimensional framework that captures the quality, reliability, and affordability of energy services [11]. The Multi-Tier Framework (MTF), developed by the World Bank and other international organisations, provides a comprehensive approach to measuring energy access across six key attributes [11].

The electrification rate represents the fundamental metric of the proportion of households or populations with access to electricity. While essential for tracking progress, this indicator alone fails to capture the quality or utility of the connection [12]. Studies have shown significant variations in the definitions and measurements of electrification rates across countries, with some defining any electrical connection as "electrified" regardless of service quality [11].

Availability measures the number of days electricity is available in a typical week, a critical factor for supporting productive uses and improving quality of life [2]. Hours of supply measure the number of hours of electricity available on days when supply exists. Research indicates that intermittent supply significantly reduces the developmental benefits of electrification, with households and businesses unable to rely on electricity for essential activities [13,14].

Affordability assesses the cost of electricity relative to household income, a key determinant of whether access translates into meaningful use [15]. Studies across Sub-Saharan Africa demonstrate that high electricity tariffs often lead to minimal consumption, even among connected households, limiting the poverty-reduction potential of electrification programs Graber et al. [16].

Reliability evaluates the frequency and/or duration of interruptions/outages, which are essential for both household- and community-level development [17]. Consistency of supply measures voltage and frequency stability (and related quality attributes like voltage sags/swells, flicker, harmonics) rather than "unreliable supply", which constrains productive activities, limits the operation of essential services such as health clinics and schools, and reduces overall welfare gains from electrification [18].

These indicators provide a comprehensive framework for evaluating the effectiveness of electrification interventions and their broader developmental impacts, moving beyond simple connection counts to assess the quality and utility of energy services.

Importantly, multi-tier survey evidence shows that a binary 'electrified/not electrified' metric can mask substantial service deficits: many connected rural households still face limited daily hours, low capacity, and frequent interruptions. This motivates the use of

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service-quality indicators alongside simple connection counts when assessing mini-grid performance [11,13,14].

1.2. Mini-Grids as a Solution for Rural Electrification

Mini-grids are decentralised electricity networks that serve a defined group of consumers and can operate independently or in conjunction with the main grid. They are increasingly recognised as a viable solution for rural electrification in developing countries, particularly where grid extension is economically or technically unfeasible [2,4,19]. Mini-grids can be powered by a variety of generation technologies, including diesel generators, solar photovoltaic (PV) systems, wind turbines, micro-hydro, and biomass gasifiers, with hybrid renewable energy systems (HRESs) gaining prominence due to their ability to mitigate the intermittency of renewables and enhance reliability [12,20].

Hybrid renewable energy systems, which integrate multiple renewable sources, are increasingly being deployed in mini-grids to enhance reliability, reduce costs, and minimise environmental impacts [19]. The declining costs of renewable energy technologies, particularly solar photovoltaic systems, have made mini-grids increasingly competitive with diesel-based alternatives and grid extension [21,22].

Empirical studies have demonstrated that mini-grids can significantly improve energy access indicators across multiple dimensions. Kirubi and Jacobson [23] found that community-based micro-grids in Kenya increased electrification rates from 5% to 95% in participating communities while providing 12–24 h of daily supply. Similarly, Palit and Kaushik Ranjan [3] documented improvements in availability and reliability compared to grid-connected areas in rural Bangladesh, with mini-grid customers experiencing fewer outages and more consistent supply.

The flexibility of mini-grids allows for phased development and incremental capacity additions as demand grows, making them particularly suitable for rural contexts where energy demand is initially low but expected to increase over time [24]. Furthermore, mini-grids can support productive uses of electricity, including agricultural processing, small-scale manufacturing, and commercial activities, thereby contributing to local economic development beyond basic household electrification [25].

Mini-grids are implemented through diverse ownership and management models (public/utility, private operator, community-based, and public–private partnerships), and these institutional arrangements can shape tariff acceptability, maintenance capacity, and ultimately the realised service indicators experienced by users [16,19,23,26].

1.3. Research Gap and Justification for Systematic Review

Despite a growing literature on mini-grids and rural electrification, the evidence base remains fragmented. Many studies are single-site case analyses or technology-specific assessments, and existing reviews often emphasise technical or economic performance rather than how mini-grids change user-experienced energy-access services [2,24]. Across studies, the definitions and measurement of core service attributes—such as availability, reliability, and affordability—vary substantially, constraining comparability and synthesis [11].

A second gap concerns implementation models and enabling environments. Mini-grids are deployed under diverse ownership and governance arrangements and within different regulatory and tariff regimes, yet the literature rarely assesses how these institutional choices shape service outcomes across indicators [19,26]. Where evidence exists, it suggests that operator capabilities, revenue collection, and community engagement influence reliability, hours of supply, and sustained uptake [16,23].

This systematic review is therefore warranted to consolidate peer-reviewed evidence on how mini-grids affect six energy-access indicators—electrification rate, availability, hours of supply, affordability, reliability, and consistency—across developing-country rural contexts. The review adopts a service-quality perspective: Improvements in these indicators are treated as necessary conditions for development impacts but are not assumed to translate automatically into welfare gains. By focusing on harmonisable energy-service attributes, the review aims to clarify what is known, where evidence is thin, and which contextual factors appear most consequential for realised performance [11,25].

In contrast to prior mini-grid reviews that focus primarily on technology performance or connection outcomes, this review synthesises evidence using a consistent six-indicator, service-quality lens (availability, hours, affordability, reliability, and consistency alongside electrification). By pairing this framework with a mixed-methods-compatible quality appraisal, the review clarifies which indicator claims are supported by extractable quantitative evidence versus qualitative or proxy reporting.

1.4. Research Question and Objectives

The central research question guiding this systematic review is: "What does the academic literature reveal about the impact of mini-grids on rural energy-access indicators (electrification rate, availability, hours of supply, affordability, reliability, and consistency) in developing countries?"

To address this question, the study pursues the following specific objectives:

1. To systematically identify peer-reviewed empirical studies on mini-grids and rural energy access in developing countries, ensuring comprehensive coverage of relevant studies across different databases and publication types.
2. To assess the impact of mini-grids on key energy access indicators, including electrification rate, availability, hours of supply, affordability, reliability, and consistency, using standardised frameworks where possible.
3. To analyse the factors influencing the effectiveness of mini-grids in improving energy access, including technological configurations, ownership models, regulatory frameworks, and community characteristics.
4. To identify gaps in the current literature and propose directions for future research and policy, highlighting areas where additional evidence is needed to inform decision-making.

1.5. Paper Structure Overview

To address the research question, the paper is organised as follows. Section 2 describes the systematic review protocol, search strategy, eligibility criteria, study selection, and quality appraisal approach. Section 3 presents the results, including descriptive characteristics of the included studies, and a narrative synthesis across the six energy-access indicators. Section 4 discusses cross-indicator patterns, contextual determinants of performance, research gaps, and policy-relevant implications. Section 5 concludes with a concise summary of key findings, contributions, and directions for future research. Supplementary extraction and appraisal materials are provided in Appendix A.

2. Materials and Methods

This section describes the methodological approach used to conduct the systematic review. It outlines the review protocol, database search strategy, eligibility criteria, study selection process, data extraction procedures, and quality assessment framework adopted to synthesise empirical evidence on mini-grid impacts across energy access indicators. The methodology is designed to ensure transparency, reproducibility, and alignment with PRISMA 2020 guidelines.

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2.1. Review Design

This study adopts a systematic literature review design guided by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework [27,28]. The review focuses on empirical studies examining the impacts of mini-grid electricity systems on energy-access outcomes in rural areas of developing countries. A systematic approach was employed to ensure transparency, replicability, and comprehensive coverage of the relevant literature.

Protocol registration: The review protocol was registered in INPLASY (International Platform of Registered Systematic Review and Meta-Analysis Protocols) (Registration No.: INPLASY202510032; https://doi.org/10.37766/inplasy2025.1.0032). PRISMA checklist: A completed PRISMA 2020 checklist is provided in Table A1.

2.2. Search Strategy and Databases

Boolean operators and truncations were used to maximise retrieval while maintaining relevance. The full search strings used for each database are provided in Table 1.

Table 1. Database search strings used for literature identification.

Databases	Search Strings
Web of Science	TS = ((“mini-grid” OR “minigrid” OR “mini grid” OR “micro-grid” OR “microgrid” OR “micro grid” OR “off-grid” OR “Offgrid” OR “off grid” OR “decentralised energy” OR “decentralized generation” OR “distributed generation” OR “distributed generation” OR “standalone power system” OR “standalone power systems” OR “hybrid renewable energy system” OR “hybrid renewable energy systems” OR “rural electrification”) AND (“electrification rate” OR “energy access” OR “electricity access” OR “energy availability” OR “days of availability” OR “electricity supply” OR “hours of electricity” OR “hours of supply” OR “affordable electricity” OR “electricity affordability” OR “tariff” OR “tariffs” OR “reliable electricity” OR “power reliability” OR “supply reliability” OR “energy consistency” OR “supply consistency” OR “energy performance” OR “power quality” OR “electricity service” OR “energy service” OR “power supply” OR “power service” OR “electricity connection” OR “energy outcomes” OR “connection” OR “electricity usage”) AND (“impact” OR “effect” OR “effects” OR “influence” OR “outcome” OR “outcomes” OR “evaluation” OR “assessment” OR “performance”) AND (“empirical” OR “case study” OR “case-study” OR “field data” OR “primary data” OR “cohort” OR “cohort study” OR “survey” OR “household survey” OR “interview” OR “mixed-method” OR “mixed methods” OR “observational”) AND (“rural” OR “rural area” OR “rural areas” OR “remote community” OR “remote communities” OR “rural village” OR “rural villages” OR “off-grid village” OR “off-grid villages” OR “peri-urban area” OR “peri-urban areas”) AND (“developing country” OR “developing countries” OR “low-income country” OR “low-income countries” OR “middle-income country” OR “middle-income countries” OR “low- and middle-income countries” OR “LMIC” OR “LMICs” OR “Sub-Saharan Africa” OR “South Asia” OR “global south” OR “emerging economy” OR “emerging economies”) NOT (“solar home system” OR “solar home systems” OR “SHS” OR “simulation” OR “simulations” OR “urban” OR “urban area” OR “urban areas” OR “systematic review” OR “meta-analysis” OR “developed country” OR “developed countries” OR “high-income country” OR “high-income countries” OR “OECD” OR “Europe” OR “North America” OR “USA” OR “United States” OR “Canada” OR “Australia” OR “Japan” OR “South Korea” OR “UK” OR “New Zealand” OR “European Union” OR “EU”)) and Article or Review Article (Document Types) and 2025 or 2024 or 2023 or 2022 or 2021 or 2020 or 2019 or 2018 or 2017 or 2016 or 2015 or 2014 or 2009 or 2008 or 2007 or 2005 (Publication Years) and English (Languages)
SCOPUS	TITLE-ABS-KEY ((“mini-grid” OR “mini-grids” OR “microgrid” OR “microgrids” OR “off-grid” OR “decentralised energy” OR “decentralized energy” OR “standalone power system” OR “standalone power systems” OR “hybrid renewable energy system” OR “hybrid renewable energy systems” OR “rural electrification”) AND (“electrification rate” OR “energy access” OR “electricity access” OR “energy availability” OR “days of availability” OR “electricity supply” OR “hours of electricity” OR “hours of supply” OR “affordable electricity” OR “electricity affordability” OR “tariff” OR “tariffs” OR “reliable electricity” OR “power reliability” OR “supply reliability” OR “energy consistency” OR “supply consistency” OR “energy performance” OR “power quality” OR “electricity service” OR “energy service” OR “power supply” OR “power service” OR “electricity connection” OR “energy outcomes” OR “connection” OR “electricity usage”) AND (“impact” OR “effect” OR “effects” OR “influence” OR “outcome” OR “outcomes” OR “evaluation” OR “assessment” OR “performance”) AND (“empirical” OR “case study” OR “case-study” OR “field data” OR “primary data” OR “cohort” OR “cohort study” OR “survey” OR “household survey” OR “interview” OR “mixed-method” OR “mixed methods” OR “observational”) AND (“rural” OR “rural area” OR “rural areas” OR “remote community” OR “remote communities” OR “rural village” OR “rural villages” OR “off-grid village” OR “off-grid villages” OR “peri-urban area” OR “peri-urban areas”) AND (“developing country” OR “developing countries” OR “low-income country” OR “low-income countries” OR “middle-income country” OR “middle-income countries” OR “low- and middle-income countries” OR “LMIC” OR “LMICs” OR “Sub-Saharan Africa” OR “South Asia” OR “global south” OR “emerging economy” OR “emerging economies”) AND NOT (“solar home system” OR “solar home systems” OR “SHS” OR “simulation” OR “simulations” OR “urban” OR “urban area” OR “urban areas” OR “systematic review” OR “meta-analysis” OR “developed country” OR “developed countries” OR “high-income country” OR “high-income countries” OR “OECD” OR “Europe” OR “North America” OR “USA” OR “United States” OR “Canada” OR “Australia” OR “Japan” OR “South Korea” OR “UK” OR “New Zealand” OR “European Union” OR “EU”)) AND PUBYEAR > 2004 AND PUBYEAR < 2026 AND (LIMIT-TO (DOCTYPE, “ar”) OR LIMIT-TO (DOCTYPE, “re”)) AND (LIMIT-TO (LANGUAGE, “English”)

2.3. Eligibility Criteria

Table 2 presents the eligibility criteria used to identify studies examining the impact of mini-grids on rural energy-access indicators in developing countries. These criteria were designed to ensure that only empirical, field-based studies focusing on real-world mini-grid interventions were included, and that they reported at least one of the six core indicators relevant to this review: electrification rate, availability, hours of supply, affordability, reliability, and consistency. By applying these criteria, the review ensured methodological rigour, contextual relevance, and alignment with the overarching research question on how mini-grids influence energy access in rural developing countries.

Table 2. Screening eligibility checklist (include/exclude criteria).

Criterion Type	Criterion	Include If...	Exclude If...
Population	Rural developing-country setting	Rural communities in developing countries	Developed countries contexts
Intervention	Mini-grid/off-grid, micro-grid	System deployed and operating	Focusing on SHS, grid extension, and generator-only
Study Design	Empirical, field-based	Primary or real operational data	Simulation/optimisation only
Outcomes	Reports at least one of six indicators	Electrification rate, availability, hours, reliability, consistency, affordability	No measurable energy-access indicators
Time Frame	2005–2025	Publication within range	Before 2005
Publication Type	Peer-reviewed	Journal or peer-reviewed conference	Thesis, blog, report, book chapter
Accessibility	Full text available	Full PDF retrievable	No access/abstract only
Language	English	English full text	Non-English

2.4. Study Selection Process

The initial database search yielded 138 records. After automated and manual de-duplication, 96 unique titles and abstracts were screened for relevance. At this stage, 26 studies were excluded if they did not focus on mini-grids or failed to report energy-access outcomes.

Following title and abstract screening, 70 full-text articles were assessed for eligibility. Of these, 22 studies met all inclusion criteria and were retained in the final synthesis. The study selection process is documented using a PRISMA flow diagram (Figure 1).

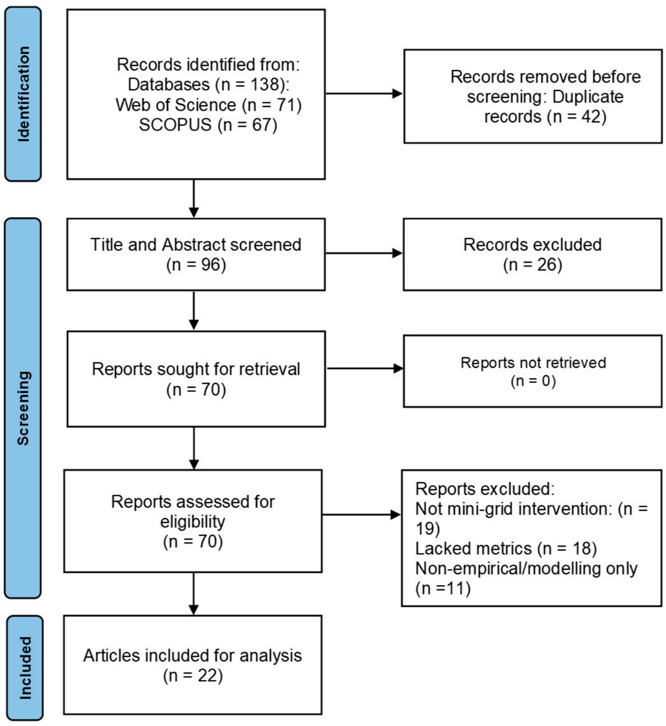

Figure 1. PRISMA flow diagram of study selection.

2.5. Data Extraction and Quality Assessment

For this review, data extraction was conducted using a structured form designed to capture all relevant elements for assessing the impact of mini-grids on rural energy access indicators. The extraction form recorded: (1) bibliographic information (authors, year, journal, country); (2) study design and methodological details (quantitative, qualitative, or mixed-methods; sampling strategy; sample size); (3) geographic and infrastructural context (country, rural setting, type of mini-grid system deployed); (4) the specific energy-access indicators reported, such as electrification rate, availability, hours of supply, reliability, consistency, and affordability, including how each indicator was defined, measured, and validated; and (5) the study's treatment of electricity access in relation to wider rural development outcomes.

The quality appraisal of studies included in the mini-grid review employed a mixed-methods-compatible assessment framework to evaluate methodological rigour, transparency, and relevance to the energy-access indicators under investigation (Table 3). Quality appraisal used a 10-criterion checklist scored on a 0–2 scale (0 = not reported/weak, 1 = partially addressed, 2 = clearly addressed with sufficient detail). Criterion scores were summed to a total (0–20). Studies were not excluded solely because of a low-quality score; instead, quality results are used to interpret confidence in indicator findings and to highlight methodological gaps in the evidence base.

Table 3. Quality appraisal template (mixed-methods compatible).

Criteria	Question	Score (0–2)
Research clarity (Q1)	Are objectives and research questions clearly stated?	
Study design relevance (Q2)	Is the study design appropriate for assessing mini-grid impacts (e.g., before–after, with–without, quasi-experimental, robust causal logic)?	
Sampling adequacy (Q3)	Is the sampling strategy (households, systems, communities) justified, adequate, and appropriate?	
Context transparency (Q4)	Are the country, rural setting, community name, mini-grid type, ownership model, size, tariff, and deployment period clearly described?	
Outcome validity (Q5)	Are energy-access indicators (electrification rate, availability, hours, affordability, reliability, consistency) well-defined and measured validly?	
Measurement reliability (Q6)	Field/operational data vs. recall vs. estimates?	
Bias/confounding control (Q7)	Are confounders/comparison groups addressed?	
Analytical rigour (Q8)	Appropriate statistics or reasoning used?	
Ethical and funding transparency (Q9)	Ethics, consent, and funding disclosed?	
Generalisability (Q10)	Do findings plausibly transfer beyond the immediate case study context?	

Each study was assessed against ten criteria, including clarity of research objectives, suitability of the study design, sampling adequacy, contextual reporting, validity of the outcomes, data-source reliability, bias control, analytical rigour, ethical transparency, and generalisability. This appraisal ensured that only studies providing credible, well-defined evidence on electrification, availability, hours of supply, affordability, reliability, or consistency were synthesised, thereby strengthening the robustness of the overall findings.

Synthesis approach: Given substantial heterogeneity in study designs, contexts, and indicator definitions, we conducted a narrative synthesis structured around the six pre-specified energy-access indicators. Because no meta-analysis was performed, we did not undertake quantitative reporting-bias assessments (e.g., funnel plots) or GRADE certainty ratings; instead, the structured quality appraisal was used to interpret confidence in the direction and robustness of reported findings.

3. Results

This section synthesises empirical evidence from 22 peer-reviewed studies published between 2005 and 2025 on the performance of renewable-dominant rural mini-grids in developing countries. After describing the search yield and eligibility process, we characterise the literature landscape (Section 3.1) before assessing impacts on six energy-access indicators: electrification rate, availability of supply, hours of supply, affordability, reliability, and consistency (Sections 3.2.1–3.2.6). Section 3.3 examines how these outcomes vary across geographies and technologies, and Section 3.4 summarises the methodological quality of the evidence base. To support cross-study comparability, we applied the indicator definitions and harmonisation rules in Table 4 when extracting and interpreting evidence.

Table 4. Indicator dictionary and harmonisation rules used in the synthesis.

Indicator	Conceptual Boundary	Preferred Standardised Metric	How We Treated Heterogeneous Reporting
Electrification rate	Access/connection outcome (whether a household/community has electricity access)	% of households or population with electricity access (clearly defined denominator)	When studies reported only connection counts or enrolment/uptake, we reported these as coverage proxies and noted denominator limitations.
Availability of supply	Whether electricity is available across days (temporal availability)	Days per week with electricity available (days/week)	We prioritised extractable days/week; when only qualitative statements were provided (e.g., 'often available'), we coded as qualitative evidence and did not treat as comparable to quantified measures.
Hours of supply	Daily duration of electricity on supply days	Hours per day (h/day) or hours/day by season	We prioritised extractable hours/day; where reported as evening-only or time windows, we converted to approximate hours/day and flagged as proxy (time window-based).
Affordability	Cost burden relative to households/enterprises and ability to pay	Tariff (USD/kWh) and/or monthly expenditure (USD/month) and/or affordability ratio (% income)	We extracted tariffs/expenditures when provided; where affordability was discussed only via willingness-to-pay or perceptions, we reported qualitatively and avoided pooling across incomparable metrics.
Reliability	Frequency/duration of outages/interruption events (continuity of service)	Outage frequency and duration (SAIFI/SAIDI or equivalent)	Because SAIDI/SAIFI were rarely reported, we extracted any quantified outage frequency/duration; categorical reliability bands (e.g., days/month without supply) were treated as semi-quantitative evidence.
Consistency (power quality)	Voltage/frequency stability and related power-quality attributes	Voltage and frequency statistics (e.g., mean, range, % time within bands)	No included study reported standardised voltage/frequency metrics. Proxy evidence (e.g., peak-demand stress windows) was reported narratively but not treated as a power-quality measurement.

3.1. Descriptive Analysis of Included Studies: A Summary Is Provided in Table 5

Table 5 presents descriptive characteristics of included studies (n = 22). The 22 included studies are distributed across 19 distinct academic outlets, indicating a relatively dispersed publication landscape. The ten most frequent journals account for approximately 61% of the corpus (n = 14/22). *Energy for Sustainable Development* emerges as the most prominent outlet (n = 3), followed by *Energies* (n = 2) and *Environmental Research: Infrastructure and Sustainability* (n = 2). All remaining journals are represented by a single study each, including *Energy Research & Social Science*, *Energy Policy*, *Development Engineering*, *Renewable and Sustainable Energy Reviews*, and *Science Advances*, among others. Geographically, the evidence base is concentrated in Africa (n = 13; 59.1%) and Asia (n = 8; 36.4%), with one study in Latin America (n = 1; 4.5%). Methodologically, mixed-methods designs dominate (n = 12; 54.5%), followed by quantitative studies (n = 9; 40.9%) and one qualitative study (n = 1; 4.5%). In terms of technology, solar PV–battery mini-grids are most common (n = 9; 40.9%), followed by solar PV–diesel hybrid systems (n = 4; 18.2%), PV–wind hybrids (n = 4; 18.2%), and micro-hydropower schemes (n = 4; 18.2%); one study (n = 1; 4.5%) examines an interconnected mini-grid configuration.

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Table 5. Descriptive characteristics of included studies (n = 22).

Characteristic	Summary
Publication outlets	22 studies across 19 outlets; the ten most frequent journals account for 61% (14/22). Most frequent: *Energy for Sustainable Development* (3), *Energies* (2), *Environmental Research: Infrastructure and Sustainability* (2).
Geographic focus	Africa: 13 (59.1%); Asia: eight (36.4%); Latin America: one (4.5%).
Study design	Mixed-methods: 12 (54.5%); quantitative: nine (40.9%); qualitative: one (4.5%).
Mini-grid technology	Solar PV–battery: nine (40.9%); solar PV–diesel hybrid: four (18.2%); PV–wind hybrid: four (18.2%); micro-hydropower: four (18.2%); interconnected mini-grid: one (4.5%).

3.2. Impact on Specific Energy-Access Indicators

This section synthesises findings from the 22 included studies across six energy service indicators, using the harmonised definitions in Table 4 to maintain conceptual separation between indicators and to avoid pooling incomparable metrics. Table 6 summarises indicator coverage and highlights the remaining deficit in standardised, extractable metrics, particularly for reliability and power quality. A detailed Study-level mapping of reported energy-access service indicators is provided in Table A2.

Table 6. Coverage of energy-access indicators and deficit in standardised metrics (n = 22).

Indicator	Studies Reporting Indicator (n)	Coverage (%)	Standardised, Cross-Study Metric Availability
Electrification rate	10	45.5	Often reported as connection/uptake, population-referenced rates are inconsistently defined.
Availability of supply (days/week)	9	40.9	Days/week reported in a minority; qualitative descriptions common.
Hours of supply (h/day)	12	54.5	Hours/day are often extractable, but measurement windows and seasonality vary.
Affordability	16	72.7	Tariffs/expenditures reported with heterogeneous currencies/units; affordability ratios are rarely comparable.
Reliability of supply	4	18.2	SAIDI/SAIFI are rarely reported; outage frequency/duration is often missing or categorical.
Consistency (power quality)	0	0.0	No standardised voltage/frequency statistics reported; only proxy evidence in narrative form.

3.2.1. Electrification Rate

Across the final screened corpus (n = 22 studies), 10 studies explicitly report electrification outcomes, typically as electrification rates and/or numerical connection counts for installed rural mini-grids. In line with Table 4, connection counts without a clearly stated denominator are treated as coverage proxies rather than population-referenced electrification rates.

Baseline or pre-intervention electrification levels are reported in several studies. On Cobrador Island, Philippines, household electrification prior to the hybrid mini-grid intervention stood at 55% (138 of 250 households) [29]. In the Sundarbans, India, solar mini-grid villages exhibited low household electrification rates of 21.0% in Bagdanga and 18.5% in Baliara, substantially below nearby grid-connected villages [30].

Village-scale case studies often report high but incomplete coverage. In Bulongwa, Tanzania, the mini-hydropower scheme connects 264 households and 82 businesses, which the authors estimate represents approximately 80% of village households [31]. In Magiro, Kenya, an off-grid mini-hydropower system supplies electricity to around 200 households, although no percentage coverage is provided [32].

Several studies report absolute connection counts without population denominators. A cohort study of 22 solar mini-grids in Kenya and Nigeria documents 2658 connected customers (households and commercial users) one year after commissioning [33]. In Habaswein, Kenya, the number of connected customers increased from approximately 700 to 1800 over a five-year period [34].

Where population context is provided, connection counts can indicate partial but meaningful coverage. In Gbamu-Gbamu, Nigeria, a solar–diesel hybrid mini-grid supplies 220 residential and 83 non-residential customers in a village of approximately 5000 inhabitants, indicating partial coverage [35]. In Yebu, Nigeria, the community solar mini-grid is reported to serve approximately 5000 people [36]. In Sierra Leone, a solar hybrid mini-grid serves 228 connected households and small enterprises in a township of around 3800 people [37].

Experimental and quasi-experimental designs report relative changes in electrification. A randomised controlled trial of off-grid solar DC mini-grids in rural India finds a 29–36 percentage-point increase in household electrification in treated habitations compared with controls [38]. In rural Rajasthan, India, 77% of surveyed households report being connected to a solar micro-grid for lighting and appliance use [39].

A comparative evaluation of rural electrification options in Chiapas, Mexico, reports concrete connection numbers for case-study projects, including 24 houses and three schools under grid extension and approximately 46 and 12 households under wind–PV micro-grids [40].

3.2.2. Availability of Supply (Days per Week)

Across the final screened corpus (n = 22 studies), nine studies quantify availability of supply in ways that can be expressed as days per week, either by stating weekly availability directly (e.g., "7 days/week"), describing 24/7 operation, reporting "nearly 365 days/year," or presenting appliance-specific days-per-week access.

Among studies that report this metric explicitly, electricity availability is most commonly described as seven days per week, although this does not imply continuous supply throughout the day. For example, solar and hybrid mini-grids in the Philippines and Tanzania are reported to operate on all days of the week, despite experiencing load-shedding or restricted evening service windows [29,31]. Experimental off-grid solar micro-grids in rural India similarly provide electricity every day, but only during limited evening hours [38]. In southern Ethiopia, availability is framed as operating on all days, but with substantial daily shortfalls (i.e., "7 days/week but not 24 h/day"), highlighting that weekly availability can coexist with constrained delivery [41].

Some studies quantify weekly availability through end-use differentiation. In Kenya, Mwaniki et al. [32] report appliance-specific patterns. For example, lighting is available 7 days/week, but fewer days for televisions and higher-load commercial appliances (e.g., ~5 days/week for TVs and ~2–3 days/week for some commercial uses). In Uganda, Cartland et al. [42] report daily availability for basic services such as lighting and radio use, with fewer days of access for higher-load appliances.

Several additional studies imply near-continuous availability without quantifying days per week. The hybrid diesel–PV–wind mini-grid in Habaswein, Kenya, is reported to supply electricity for "nearly 365 days per year," suggesting uninterrupted daily operation, although no explicit weekly metric is provided [34]. Other studies report 24/7 availability, which is operationally equivalent to seven days per week, including systems described as continuous in Nigeria and India [35,39]. Island mini-grids in Ghana are similarly described as 24/7 systems, even if the reporting does not state "days/week" explicitly [43].

3.2.3. Hours of Supply (Hours per Day)

Hours of electricity supply per day are explicitly reported in 12 of the 22 studies, either as explicit service hours, categorical supply bands, or closely related quantitative proxies (e.g., monitored interval load data or lighting-hour measures).

Where reported, daily hours of supply vary substantially across contexts and system designs. Several studies document near-continuous or 24 h supply following mini-grid installation. On Cobrador Island in the Philippines, electricity availability increases from approximately 8 h per day to 24 h per day after commissioning of a hybrid solar–battery–diesel mini-grid [29]. Community-owned solar micro-grids in rural India are similarly described as providing 24 h/day electricity to connected households [39], while solar–diesel hybrid mini-grids in southwest Nigeria are reported to operate on a 24/7 basis, supporting both household and productive uses [35].

In contrast, many mini-grids deliver partial-day supply, particularly during evening hours. Experimental solar DC micro-grids in rural India provide approximately 5 h per day of evening electricity [38]. Solar mini-grids in the Sundarbans region of India supply around 5 h per day to connected households, compared with 20–22 h per day in nearby grid-connected villages [30]. In Kenya, off-grid mini-hydropower and institutional schemes report between 4 and 12 h per day, depending on the site and end use [32]. A cohort study in Kenya and Nigeria reports improvements in lighting duration from ~4 h/day to ~7 h/day following mini-grid commissioning [33].

Several studies highlight severe constraints on daily supply despite nominal system operation. In southern Ethiopia, a monitored PV–battery–diesel mini-grid supplies electricity for only approximately 11 h per day, with reported load shedding of around 13 h per day due to demand–capacity mismatch [41]. In Nepal, analysis of 12 community-managed micro-hydro schemes shows that around half operate for 20 h per day or less, while only four provide continuous 24 h operation [44]. In Tanzania, hours are reported as <24 h/day with frequent evening restrictions [31].

Other studies report categorical or differentiated supply durations rather than single numeric values. Community-owned solar mini-grids in India are similarly classified into discrete supply bands (e.g., 4, 8, 16, or 23 h per day), reflecting Multi-Tier Framework-aligned service levels rather than continuous metrics [45]. One study quantifies delivered lighting service as lumen-hours/day (44,924–65,288 lumen-hours/day), capturing "usable" lighting supply rather than electricity hours alone [46]. In Sierra Leone, one study uses a full year of 1 h interval load data to characterise delivery patterns [37], while another reports daily average energy production (~42.31 kWh/day), which supports inference with respect to service provision, but is not a direct "hours/day" statistic [47].

3.2.4. Affordability

Affordability of electricity supply is reported in 16 of the 22 studies, using tariffs (per kWh or fixed charges), household electricity expenditures (weekly/monthly), willingness-to-pay comparisons, connection fees, and/or cost-of-supply metrics. Key affordability measures and illustrative examples are summarised in Table 7.

Where reported, affordability outcomes vary widely across contexts and system designs. On Cobrador Island in the Philippines, electricity tariffs of approximately PHP 15/kWh (USD 0.29/kWh) represent a 50% reduction relative to pre-project energy costs [29]. In Bulongwa, Tanzania, households connected to a micro-hydropower mini-grid pay a flat monthly fee of approximately TZS 7000 (USD 2.84/month), while small businesses pay TZS 10,000–30,000 (USD 4.06–12.18/month), significantly lower than previous diesel-based alternatives [31]. Similar expenditure reductions are reported in Kenya, where mini-hydropower households reduce average daily energy spending from KSh 110/day to KSh 7/day (USD 25.58–1.63/month) [32].

Experimental and quasi-experimental studies report modest but measurable electricity costs. In rural India, solar DC micro-grids charge a flat tariff of INR 100/month (USD 1.50/month) for basic evening supply [38], while solar mini-grid households in the Sundarbans pay ₹75–135/month (USD 1.15–2.10/month) for approximately five hours of daily supply [30].

Other studies quantify affordability via expenditure distributions and observed spending. In Uganda, most solar mini-grid users spend UGX 10,000/month (USD 2.83/month), although higher-use households pay up to UGX 80,000–100,000/month (USD 22.62–28.27/month), with reported tariffs of approximately UGX 1000/kWh (USD 0.28/kWh) [42]. In Tanzania, weekly household electricity expenditure is reported as approximately TSh 2000–5000/week [46]. In Mexico, example household bills of approximately US$1.5–2.5/month are reported, with the micro-grid option noted as heavily subsidised [40]. In Nepal, tariffs are expressed as approximately US$0.007 per watt of connected load [48].

A subset of studies quantifies affordability through high tariffs, willingness-to-pay gaps, and cost-of-supply measures. In a remote island mini-grid in Tanzania, electricity prices of TZS 3500/kWh (EUR1.30/kWh) substantially exceed stated willingness to pay, limiting household-level consumption despite positive institutional and commercial impacts [47]. Broader evidence reports tariffs in the range of approximately 0.5–1.5 USD/kWh and uses affordability ratios benchmarked to GDP per capita [49]. One system-level study reports operational cost of supply ~0.30–0.85 USD/kWh, illustrating cost pressures that can translate into high retail tariffs in remote contexts [34].

Table 7. Summary of affordability metrics and illustrative values reported in the included studies.

Metric Type	Illustrative Values/Examples (as Reported)	Interpretation for Cross-Study Comparison
Tariff (per kWh)	PHP 15/kWh (USD 0.29/kWh) in the Philippines; TZS 3500/kWh (EUR 1.30/kWh) in remote island Tanzania; tariffs reported in the range of ~0.5–1.5 USD/kWh in multi-study evidence [29,47,49].	Tariffs are comparable in principle (currency/unit harmonisation needed) but often reflect context-specific costs/subsidies.
Flat monthly fee/package pricing	TZS 7000/month for households and TZS 10,000–30,000/month for small businesses in Tanzania [31]; INR 100/month for basic evening supply in rural India [38]; ₹75–135/month in the Sundarbans [30].	Flat fees depend on the included service level (hours/loads) and are not directly comparable without a service bundle specification.
Household expenditure (weekly/monthly)	UGX 10,000/month typical users; up to UGX 80,000–100,000/month higher-use households; tariff ~UGX 1000/kWh (USD 0.28/kWh) [42]; Tanzania: ~TSh 2000–5000/week [46].	Expenditures reflect both price and consumption; comparisons require consumption context and currency harmonisation.
Cost reduction versus baseline energy spending	Kenya: average daily energy spending reduced from KSh 110/day to KSh 7/day [32]; Philippines: ~50% reduction relative to pre-project costs [29].	Baseline comparisons provide within-study affordability gains but are sensitive to baseline fuel choice and counterfactual assumptions.
Tariff design and subsidies	Ghana: sustainable tariff of 10 GHS with 5.7 GHS subsidy [43]; Sierra Leone: lifeline tariff (≤3 kWh/month at 1500 SLL/kWh), connection fee 150,000 SLL, 2% annual escalator [37]; Nigeria: packages, e.g., 15 kWh/month for NGN 1500 [35].	Tariff structure shapes affordability across user groups; subsidy and connection-fee treatment must be reported for comparability.

A smaller set of studies examines affordability through structured tariff systems and subsidies. In Ghana, a "sustainable tariff" of 10 GHS and a subsidy of 5.7 GHS are reported, illustrating how subsidy design shapes affordability [43]. In Sierra Leone, affordability is quantified via a lifeline tariff (≤3 kWh/month at 1500 SLL/kWh), a connection fee of 150,000 SLL, and a 2% annual tariff escalator [37]. In Nigeria, tariff packages (e.g., 15 kWh/month for NGN 1500) are reported, reflecting bundled access for different consumption levels [35].

3.2.5. Reliability of Supply

Reliability of electricity supply is explicitly reported in four of the 22 studies, either through quantified outage frequency, duration of interruptions, or structured categorical indicators. The remaining studies address reliability indirectly through user perceptions, proxy indicators (e.g., generator displacement), or qualitative descriptions of unstable service.

Among studies reporting quantitative or semi-quantitative reliability indicators, substantial variation is observed. In Bulongwa, Tanzania, the micro-hydropower mini-grid experiences one to two outages per day, particularly during evening peak demand, with reported power cuts occurring almost daily between 19:00 and 20:30 [31]. In southern Ethiopia, detailed system monitoring shows severe reliability constraints. The PV–battery–diesel mini-grid in Omorate records approximately 13 h per day of load shedding, implying only around 11 h of effective supply and sustained unmet demand as customer numbers increase [41].

Community-owned solar mini-grids in India are similarly classified into discrete reliability bands (e.g., no outages, 1–2 days/month, 2–5 days/month, 5 days/month), consistent with Multi-Tier Framework-aligned assessment approaches [45].

3.2.6. Consistency of Supply (Power Quality)

Across the final screened corpus (n = 22 studies), no study reports standardised voltage/frequency power-quality metrics suitable for cross-study comparison. One study provides proxy evidence of time-bound service instability (e.g., peak-demand stress windows), but this is not treated as a power-quality measurement under the harmonisation rules in Table 4.

In Uganda, consistency constraints are quantified indirectly through reported system stress timing, with peak pressure occurring between approximately 17:00 and 22:00 (5–10 pm) and inability to meet peak demand consistently, indicating time-bound service instability rather than measured voltage/frequency deviations [42].

3.3. Geographic and Technological Variation

Marked geographic and technology-pattern differences emerge across the included evidence base (n = 22). Sub-Saharan Africa contributes the largest share of installed mini-grid case evidence in this corpus, spanning solar PV, hybrid PV–battery–diesel systems, and renewable–diesel–wind hybrids in Kenya, Nigeria, Tanzania, Uganda, Sierra Leone, Ghana and Ethiopia [33–37,41–43,47,49,50].

Across the corpus, reported service performance spans near-continuous provision and heavily constrained supply. In Sub-Saharan Africa, near-continuous service is reported in some systems (e.g., 24/7 operation in rural Nigeria), while other cases document constrained supply linked to storage limits and operational stress [35,41,42,47]. In the Philippines, the island mini-grid comparator case reports a shift from limited-hour service to 24 h availability post-intervention [29]. Portfolio-scale developer evidence further suggests that operational practices and digital monitoring capacity are treated as part of the reliability story, even when standard outage and power-quality indices are not formally reported [50].

South Asia in this corpus is represented entirely by India and Nepal, and it presents a distinct mix of low-capacity, evening-only solar micro-grids alongside community-managed micro-hydro schemes. Experimental and quasi-experimental evidence from India shows that decentralised systems can expand electrification and deliver predictable, limited-hour services under basic supply designs [38], while other Indian case studies report either continuous service claims in small solar micro-grid deployments or explicitly low daily hours in solar mini-grid villages when contrasted with longer-hour but voltage-problematic grid supply [30,39]. Nepal's micro-hydro evidence is strongly governance- and operations-facing: systems are frequently described as daily-operating assets, but their realised service levels vary across schemes, reflecting maintenance capacity and institutional arrangements rather than only resource availability [44,48].

South-East Asia and Latin America appear only as a small set of cases in this corpus, but they add useful contrast on planning choices and community-scale justice dynamics. In the Philippines, a hybrid island mini-grid case is associated with a documented shift from limited-hour service to full-day availability alongside tariff changes, highlighting how technology choice and operational configuration can translate into large changes in experienced service [29]. In Indonesia, qualitative and mixed-method evidence emphasises that "installed capacity" does not automatically translate into equitable or reliable access across villages and hamlets, particularly where governance and maintenance are weak [51]. In Mexico, a comparative planning evaluation explicitly places renewable micro-grids alongside grid extension and solar home systems, treating service quality and continuity as appraisal criteria rather than observed operational outcomes, and illustrating how mini-grids are positioned within wider electrification option sets [40].

Technologically, solar PV-based mini-grids dominate the installed evidence in this corpus, commonly paired with batteries and, in several African cases, diesel backup to manage variability and peak loads [35,37,41–43]. Hybridisation case studies, including diesel–PV–wind configurations and PV–battery–diesel systems, analysed systems through measured load or multi-year operational datasets [34,37]. Micro-hydro remains prominent in mountainous or high-head contexts (Nepal) and in specific African rural schemes (Tanzania; Kenya), and is generally presented as capable of daily provision but vulnerable to operational fragility, governance constraints, and demand-management pressures [31,32,44,48]. A small but methodologically important subset of studies focuses less on household welfare outcomes and more on system operation, bankability and monitoring, linking mini-grid performance to load composition, remote monitoring, and operational decision-making rather than only connection counts or user perceptions [34,37,50]

3.4. Quality Assessment of Included Studies

A structured quality appraisal was conducted for all 22 studies included in the final synthesis, using ten criteria covering research clarity, study design relevance, sampling adequacy, contextual transparency, outcome validity, measurement reliability, bias and confounding control, analytical rigour, ethical and funding transparency, and generalisability. Scores were assigned on a 0–2 scale for each criterion, yielding a maximum possible score of 20 per study (Table A3). Table 8 summarises the distribution of scores across criteria.

Table 8. Quality appraisal of included studies.

Quality Dimension	Evidence from the Assessment	Interpretation
Research clarity (Q1)	22/22 scored 2	Consistently strong articulation of objectives and interventions
Study design relevance (Q2)	10/22 scored 2	Less than half use designs suited to causal inference
Sampling adequacy (Q3)	3/22 scored 2	Sampling transparency is a major weakness
Context transparency (Q4)	16/22 scored 2	Generally rich contextual descriptions
Outcome validity (Q5)	4/22 scored 2	Many report outcomes, but few use well-defined/harmonised metrics
Measurement reliability (Q6)	6/22 scored 2	Stronger where monitored or survey data are used
Bias/confounding control (Q7)	6/22 scored ≥1	Bias is rarely addressed explicitly
Analytical rigour (Q8)	11/22 scored 2	Stronger in experimental/quasi-experimental/cohort designs
Ethical & funding transparency (Q9)	21/22 scored ≥1	Usually reported, but depth varies
Generalisability (Q10)	22/22 scored ≥1	Moderate transferability across contexts

Overall, the methodological quality of the evidence base is moderate to high, though uneven across dimensions. Research clarity is consistently strong: all 22 studies score 2 on Q1. Contextual transparency is also robust, with 16 studies (73%) scoring 2 on Q4, typically providing clear descriptions of the country setting, rural context, technology type, and deployment characteristics.

By contrast, several methodological dimensions remain weaker. Sampling adequacy (Q3) is a notable limitation: only three studies (14%) score 2, with most relying on small, purposive, or weakly justified samples. Bias and confounding control (Q7) is limited across the literature: only six studies (27%) score at least 1, reflecting infrequent use of counterfactuals, controls, or explicit bias-mitigation strategies.

Outcome validity and measurement reliability are mixed. Most studies engage with energy-access outcomes at some level (21/22 score ≥1 on Q5), but fewer report strongly defined and harmonised measures (4/22 score 2 on Q5). Measurement reliability (Q6) shows a similar pattern, with six studies (27%) scoring 2, typically those using monitored operational data or structured household survey measurement.

Analytical rigour (Q8) is generally moderate: 11 studies (50%) score 2, driven largely by experimental, quasi-experimental, or longitudinal cohort designs. Ethical and funding transparency (Q9) is generally reported (21/22 score ≥1), although depth varies. Generalisability (Q10) is also relatively strong (22/22 score ≥1), with many studies providing transferable insights beyond the immediate case. Based on aggregate scores, six studies (27%) are classified as high quality (≥15), 15 studies (68%) as moderate quality (11–14), and one study (5%) as lower quality (≤10).

To integrate study quality into interpretation, we examine indicator coverage by quality tier (Table 9). A simple sensitivity check excluding the single low-quality study does not materially change the overall indicator-coverage pattern, as the evidence base remains dominated by moderate-to-high quality studies.

Table 9. Quality appraisal summary and indicator coverage by study quality tier.

Quality Tier (Total Score)	Studies (*n*)	Median Total (IQR)	Indicator Coverage Within Tier (*n* Studies)
High (15–17)	6	16.5 (15.25–17.00)	Elec 2; Avail 2; Hours 4; Afford 3; Reliab 2; Consist 0
Moderate (11–14)	15	13.0 (12.00–13.00)	Elec 8; Avail 6; Hours 8; Afford 12; Reliab 2; Consist 0
Low (10–10)	1	10.0 (10.00–10.00)	Elec 0; Avail 1; Hours 0; Afford 1; Reliab 0; Consist 0

4. Discussion

This section interprets the review findings in relation to the study's research question and broader debates on rural electrification. It synthesises evidence across energy-access indicators, examines variation in mini-grid performance across contexts, and situates the findings relative to grid-extension alternatives. The discussion focuses on service-quality outcomes rather than downstream socio-economic impacts.

4.1. Synthesis of Findings Across Indicators

The six energy-access indicators reveal both strengths and systematic evidence gaps in the mini-grid literature. Across the included studies, electrification impacts are consistently positive but highly variable in scale and reporting. Mini-hydro and solar mini-grids in Tanzania, Kenya, Nepal, and India often achieve high community-level coverage when systems are well-matched to local demand. For example, Bulongwa in Tanzania reports 264 households and 82 businesses connected [31], while Nepalese community micro-hydro schemes are frequently described as achieving near-universal village coverage [48]. In contrast, larger or more dispersed communities tend to show partial but still meaningful gains, as seen in Gbamu-Gbamu in Nigeria [35]. Rigorous counterfactual evidence from rural India further supports substantial access increases. Aklin et al. [38] report large improvements in electrification relative to non-electrified controls. However, a recurring limitation is that many studies report numbers of connections or system capacity rather than population-referenced electrification rates [34,43,50], leaving uncertainty about comparable coverage levels across contexts.

Availability and operating hours show similarly strong heterogeneity. Some systems are described as providing daily or near-continuous service, including community and project-based solar micro-grids in Rajasthan [39] and upgraded hybrid systems in the Philippines [29]. In addition, evening-only service persists in some settings; for example, approximately five hours per day in the Sundarbans solar mini-grids [30] and around five hours per evening in the RCT setting in India [38]. Evidence also shows that "installed" capacity does not guarantee adequate service. For example, in Ethiopia, technical monitoring reveals severe constraints, with substantial daily unmet demand and long interruptions, implying limited effective hours of supply [41]. Several studies report extended schedules in well-managed micro-hydro schemes, including projects operating at or near 24 h in Nepal [44], although these often reflect plant operating schedules rather than standardised household service indicators.

Affordability is the most consistently reported indicator, but the measures vary widely (tariffs, expenditure, cost of supply, or willingness-to-pay). Evidence ranges from low-cost micro-hydro in Kenya [32] to very high tariffs in remote island solar PV contexts in Tanzania [47]. Tariff structures are diverse, including flat monthly charges [31,38], lifeline or tiered tariff designs [37,43], and prepaid/block packages [35]. Several studies indicate that mini-grids can reduce overall household energy expenditure by displacing kerosene, phone-charging markets, or diesel generator use [29,32,35], yet affordability tensions persist where tariffs exceed local willingness or ability to pay [42,47].

Reliability is frequently emphasised, but predominantly through qualitative reporting rather than standardised outage metrics. Common issues include load shedding during evening peaks, capacity constraints as demand grows, and operational fragility in community-managed systems [31,44,48,51]. A small subset of studies provides more explicit quantitative reliability evidence, notably technical monitoring in Ethiopia, documenting prolonged daily interruptions and unmet load [41], and structured categorical outage reporting across multiple solar mini-grids in India [45]. Even where formal SAIDI/SAIFI indices are absent, user narratives and operational accounts consistently position reliability as a central determinant of perceived system value and sustained uptake [35,42,43].

Consistency (power quality) remains severely under-reported in the included evidence base. Where mentioned, it is usually qualitative; for example, voltage drops and appliance constraints in grid-connected comparators versus perceived better quality under solar mini-grids in the Sundarbans [30], or concerns linked to inverter overload and battery depletion in Uganda [42]. Portfolio and technical studies discuss system performance and monitoring; however, rarely they report household-level voltage/frequency stability metrics [34]. Power-quality measurement remains a major blind spot, limiting robust assessment of whether mini-grids consistently deliver electricity services comparable to grid-quality supply.

Across indicators, the included evidence suggests that mini-grids can deliver meaningful improvements relative to no access or weak and unreliable grid supply. However, degree and durability of improvement are strongly context-dependent. This is shaped by technology choice, demand growth, governance, operational capacity, and tariff design [29,35,43,44].

4.2. Factors Influencing Mini-Grid Effectiveness

The effectiveness of mini-grids arises not from technology alone, but from the interplay among technical design choices, governance arrangements, and local contextual conditions. Across the reviewed studies, three groups of factors consistently shape service quality, affordability, and long-term sustainability.

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Technology configurations remain a foundational determinant of performance. Systems equipped with lithium-ion batteries generally outperform those with lead-acid storage due to higher depth-of-discharge tolerance, faster charge cycles, and longer lifetimes, which collectively reduce curtailment and help maintain service continuity during cloudy periods [50,52]. Similarly, hybrid supervisory controllers, combining rule-based dispatch with algorithmic optimisation, tend to achieve higher availability and lower effective costs than systems relying solely on simple control logic [34]. Diesel backup continues to play an important, if contested, role. In Kenya, Tanzania, and Nepal, the presence of diesel generators significantly improves availability during seasonal low-resource periods [31,44]. However, in remote areas, particularly in the Philippines, Sierra Leone, and Colombia, fuel transport costs and logistical constraints erode financial viability, reinforcing the need for renewable-dominant designs [47,53,54].

Institutional and governance arrangements are equally decisive. Professional or private operators frequently deliver more reliable and predictable service than purely community-owned models, reflecting stronger incentives for maintenance, structured billing, and more effective revenue protection [35,55]. Nevertheless, community-led or cooperative systems may exhibit greater tariff acceptability and social legitimacy, particularly in Nepal and Malawi, where shared ownership fosters participation in maintenance and tariff-setting processes [56,57]. Hybrid public–private arrangements, in which public entities own the assets and private operators manage day-to-day operations, appear promising for balancing cost recovery with accountability, although empirical evidence remains limited. Prepaid metering is one of the most consistent enablers of operational sustainability: across Kenya, Nigeria, Ghana, and Sierra Leone, prepaid systems reduce revenue leakage, facilitate load management, and lower the financial burden on operators without compromising affordability for low-income households [35,43,58].

Local contextual factors mediate technical potential, where resource feasibility directly shapes the relative attractiveness of technological configurations. For example, micro-hydro excels in Nepal and Tanzania but suffers during dry seasons [31,44], whereas solar-dominant systems perform best in high-insolation regions such as the Sahel, Kenya, and northern Nigeria. Road accessibility and terrain significantly affect operating costs, particularly where diesel components form part of the hybrid design [47]. Sociocultural norms also influence system uptake: Studies in Nepal, Malawi, and Tanzania highlight that willingness to pay and community buy-in are shaped by trust, collective action, and perceived fairness in tariff structures [56,59]. Mini-grids thus function as socio-technical assemblages in which engineering choices, institutional structures, and local conditions co-produce system performance.

4.3. Limitations and Research Gaps

While the evidence base for mini-grid performance has grown considerably over the past decade, several limitations constrain generalisation of findings across contexts. These gaps are methodological, geographical, and thematic.

A fundamental limitation concerns short monitoring periods. Most empirical studies evaluate systems within the first one to two years of operation, at a stage when components remain new, and user demand is still stabilising. Few studies capture medium- or long-term trajectories—including battery degradation, inverter failures, seasonal demand variance, or socio-economic spillovers beyond basic lighting. The absence of sustained monitoring also makes it difficult to assess long-run tariff sustainability, load growth, and the durability of governance arrangements. This short-termism restricts the generalisability of many positive performance assessments.

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A second constraint is limited attention to counterfactuals and causal inference. Only a small subset of studies uses matched comparison villages or quasi-experimental designs to isolate the specific effects of electrification. Most others rely on cross-sectional or descriptive methods that cannot disentangle the impacts of mini-grids from broader socio-economic dynamics. The near-total absence of randomised or quasi-randomised interventions reflects both ethical considerations and operational constraints, but it leaves unresolved important questions about the magnitude and distribution of socio-economic outcomes attributable to mini-grids.

A third weakness lies in the inconsistent and incomplete reporting of performance indicators. While affordability and reliability are widely discussed, only a minority of studies provide numerical values for reliability, availability, hours of supply, or voltage stability. Power quality is particularly underreported, as fewer than one-fifth of studies report data on voltage or frequency deviations, despite their importance for appliance compatibility and productive use. The absence of standardised definitions, in which "reliability" may refer to outages, unmet load, or subjective satisfaction, further complicates cross-study comparisons and meta-analysis.

The evidence is also marked by geographical and technological blind spots. Empirical studies cluster in South Asia and East Africa, with very limited representation from Central Africa, the Pacific Islands, francophone West Africa, and conflict-affected regions. Technologically, recent innovations such as second-life EV batteries, hydrogen-based backup systems, DC nanogrids, and peer-to-peer energy trading are virtually absent from field studies, despite growing policy interest. Finally, distributional and environmental dimensions remain underdeveloped. The gendered impacts of electrification, intra-household energy dynamics, and the distributional consequences of tariff structures are seldom analysed. Environmental sustainability assessments frequently omit battery end-of-life management and emissions associated with diesel operation in hybrid systems. As mini-grids scale up, these questions will become increasingly pressing.

These limitations point to a clear need for future research to adopt longitudinal designs, apply rigorous quasi-experimental evaluation, improve indicator standardisation, expand into under-studied regions and technologies, and incorporate gender and environmental justice frameworks. Doing so will enable researchers, governments, and practitioners to move beyond proof-of-concept to robust evidence on the long-term sustainability, equity, and developmental impact of mini-grids.

4.4. Implication for Theory and Practice

The findings refine energy-access theory in two ways. First, they challenge binary framings of "grid versus off-grid," illustrating a spectrum where hybrid mini-grids occupy a contingent but vital niche. Second, they highlight "access quality" as a multidimensional construct; affordability, availability, and reliability trade-offs must be jointly optimised rather than sequentially addressed. Future conceptual models should therefore integrate techno-economic optimisation with socio-institutional dynamics, treating energy access as a co-production between technology, governance, and user demand.

For practitioners and policymakers, four actionable lessons emerge. (i) Policy incentives should be performance-based, rewarding availability and reliability rather than installed capacity alone; Kenya's Results-Based Financing scheme offers a template. (ii) Tariff design should balance cost recovery with equity. Time-of-use or tiered tariffs, underpinned by prepaid smart meters, can cross-subsidise lifeline consumption while enabling productive uses. (iii) Technical standards need contextual flexibility, for example, diesel backups may remain necessary where cloud cover or fuel logistics dictate. However, emissions caps and renewable energy penetration milestones can guide gradual decarbonisation. (iv) Capacity-building, both community governance and local technician training, is indispensable for long-term sustainability; donor programmes should earmark ≥10% of capital budgets for "soft" components.

In summary, hybrid renewable mini-grids have matured into a credible and cost-effective pathway toward achieving SDG 7 in low-density rural markets, outperforming conventional grid extension on several key quality metrics. Realising their full potential will require standardised impact measurement, gender-responsive tariff design, and policy frameworks that internalise social and environmental externalities. Future research should prioritise long-term, comparative field trials and explore the synergies between mini-grids, digital finance, and emerging storage technologies.

4.5. Policy Implications and Recommendations

Building on the empirical patterns identified in the review, this section translates the findings into policy-relevant insights for governments, regulators, development partners, and investors involved in rural mini-grid deployment

4.5.1. Policy Recommendations for Governments

Governments should integrate mini-grids within national electrification plans using least-cost geospatial planning and transparent service-area designation, clarifying where mini-grids are expected to be the preferred option relative to grid extension and other decentralised alternatives. This reduces uncertainty and supports coherent technology choice within wider electrification portfolios [2,40]. Where grid extension is plausible in the medium term, establishing credible grid-arrival protocols is recommended. For example, compensation, interconnection, or asset-transfer rules can reduce regulatory risk and improve investment conditions for private and blended-finance developers.

Because the evidence shows substantial dispersion in realised service outcomes—especially in hours of supply and reliability—regulation and public support should prioritise audited service metrics rather than installed capacity or connections alone [29,38,41]. Performance-linked instruments can be designed around measurable indicators such as daily supply hours, outage frequency/duration, and system downtime, reflecting the aspects of energy access most directly experienced by users [31,41,44].

Affordability outcomes span large expenditure reductions in some contexts to prohibitive tariffs in remote and island settings, with tiered and cross-subsidised structures appearing in several studies [29,32,35,37,43,47]. Regulators should allow tariff designs that (i) protect basic consumption through lifeline blocks or targeted subsidies, (ii) enable cost recovery for sustainable operations, and (iii) permit differentiated pricing (e.g., productive-use customers cross-subsidising lifeline loads) where justified and transparent [35,37,43]. Where evidence indicates willingness-to-pay gaps, targeted connection-fee support or demand-stimulation measures may be necessary to prevent low utilisation and under-recovery [42,47].

A central gap in the evidence base is the limited and inconsistent reporting of reliability, and the near-absence of quantified power-quality metrics. Regulators and funders should require routine disclosure of (at a minimum) outage frequency and duration, plus basic voltage-quality monitoring where feasible [30,31,41,42,44]. A public reporting registry—quarterly or biannual—can improve accountability, enable benchmarking, and reduce information asymmetries that currently limit learning across projects.

Several reviewed contexts highlight operational fragility and performance erosion, where maintenance and governance systems are weak [42,44,60]. Governments can support sustainability by reducing unnecessary permitting delays (one-stop licensing, standardised templates, clear E&S screening), while enforcing minimum technical quality standards to prevent sub-par equipment that undermines service delivery.

4.5.2. Guidelines for Development Organisations and Donors

Given the heterogeneity in service quality and the limited availability of rigorous long-run evidence, development programmes should support monitoring and verification that extends beyond installation milestones, focusing on service delivery and operational performance [29,41,50]. Support mechanisms can be structured so that a portion of funding is linked to verified service outcomes (e.g., sustained hours of supply, reduced downtime), while still accommodating context-specific constraints.

Evidence from community-managed schemes and deteriorating service over time underscores the importance of maintenance capability, governance, and revenue protection [42,44,60]. Donors should allocate resources for technician training, regional service hubs, spare-parts supply chains, and operator systems (O&M procedures, fault response protocols, and financial management), complementing capital support.

Several studies indicate that productive and commercial users are central to financial sustainability and service utilisation, including where cross-subsidy models emerge [35,37]. Donor programmes can pair electrification with productive-use enablement (appliance financing, enterprise training, targeted support for anchor loads such as clinics, schools, cold storage, irrigation) to reduce demand risk and improve the economics of maintaining higher service levels.

Only a small subset of studies uses experimental, quasi-experimental, or cohort-style approaches, and many evaluations are short-term. Donors should reserve funding for longer monitoring periods and stronger evaluation designs to improve causal inference and capture trajectories such as load growth, battery degradation, and service stability [33,34,38,41].

4.5.3. Investment and Financing Considerations

The evidence shows that service quality can deteriorate as demand grows or maintenance systems fail, and that demand–capacity mismatch can result in extensive load shedding even where systems remain nominally operational [34,41,43]. Investors should therefore prioritise projects with credible demand assessments, phased capacity-expansion pathways, and evidence of operational capability.

Anchor–business–community dynamics occur across multiple contexts in which commercial users and institutions support utilisation and revenue generation [34,35,37]. Portfolio strategies should incorporate anchor-load contracting, appliance finance for productive use, and staggered capacity additions to avoid overbuilding or underserving demand.

Portfolio-level evidence highlights the role of operational practices, monitoring, and fault response, even where standard outage indices are not reported [50]. Investors should require time-series operational reporting (energy sales, downtime events, dispatch patterns, arrears/collection rates where relevant) and verify that monitoring systems and maintenance procedures are resourced.

Findings on affordability vary widely, from substantial savings to high tariffs that suppress use, implying that business models must be stress-tested against willingness-to-pay, local income variability, and tariff acceptance [29,42,43,47]. Where tariffs must remain low for equity reasons, blended finance or targeted support may be needed to preserve service quality without compromising operator viability.

4.5.4. Technology and Implementation Recommendations

The corpus includes both near-continuous and evening-only supply systems, showing that technology choice and operational configuration materially affect experienced access [29,30,38,44]. Project design should begin with explicit service targets (e.g., expected daily hours, reliability thresholds), ensuring generation, storage, and dispatch control are sized to meet realistic demand profiles.

Evidence from monitored systems and longitudinal cases shows that demand growth can create sustained unmet load and frequent interruptions if expansion pathways are not built into system design and financing [34,41]. Developers should incorporate modular expansion plans, enforce load management where appropriate, and use monitoring data to trigger timely upgrades.

Prepaid and smart metering approaches are repeatedly associated with improved billing discipline and operational sustainability in several contexts [35,43,58]. Remote monitoring and structured O&M systems can reduce downtime by enabling faster fault detection and repair, thereby supporting higher availability [50]. Because power quality is a major blind spot in the evidence base, projects should incorporate basic voltage and frequency monitoring and report these metrics transparently. Qualitative evidence suggests that mini-grids may outperform weak-grid comparators in some contexts, but the absence of standardised measurements prevents robust assessment [30,42,43].

Overall, the review suggests that renewable-dominant rural mini-grids can deliver meaningful improvements in electricity access relative to no access or weak-grid alternatives. However, outcomes depend on system design, demand trajectories, governance, tariff structures, and operational capability [29,35,41,43,44]. Policy frameworks that prioritise verified service delivery, transparent performance reporting, and affordability-aligned business models—supported by stronger operational capacity and longer-term evaluation—are most consistent with the evidence base synthesised in this review.

5. Conclusions

This systematic review reassessed what two decades of empirical research reveal about the service-quality performance of rural mini-grids—particularly solar, solar–diesel hybrid, and micro-hydropower systems—in low-income and lower-middle-income contexts. Drawing on 22 electricity-focused studies published between 2005 and 2025, we synthesised evidence across six energy-access indicators: electrification, availability, hours of supply, affordability, reliability, and power quality. Overall, mini-grids can deliver meaningful improvements in rural electricity access, but outcomes vary substantially with local demand, governance and ownership arrangements, tariff and subsidy design, and system sizing and operation. The evidence therefore supports mini-grids as a flexible electrification option, while highlighting that service-quality performance is not uniform and cannot be inferred from connection alone.

Shortcomings of this review should be acknowledged. First, despite applying a harmonised indicator dictionary, the evidence base relies on heterogeneous indicator definitions and inconsistent reporting windows, which constrained the extraction of standardised, directly comparable metrics—particularly for reliability and power quality. Second, study quality and measurement rigour vary across the corpus, meaning that some indicator claims are supported primarily by qualitative or proxy evidence rather than monitored service data. Finally, the review is limited to peer-reviewed English-language studies indexed in Scopus and Web of Science, and may therefore under-represent grey literature evaluations and operational datasets used by implementers and regulators.

5.1. Summary of Key Findings

This systematic review synthesises evidence from 22 empirically grounded studies examining rural mini-grid performance across electrification, service availability, hours of supply, affordability, reliability, and power quality.

First, mini-grids consistently expand electricity access, though coverage levels vary by settlement size, system design, and implementation context. Ten of the 22 studies report electrification rates or connection counts explicitly. Village-scale systems in Tanzania, Nepal, and Kenya frequently achieve high coverage, including approximately 80% household electrification in Bulongwa [31], and near-universal access in Sikles, Nepal [48]. In contrast, larger or more dispersed communities exhibit partial coverage, such as Gbamu-Gbamu, Nigeria, where 303 residential and non-residential connections serve a population of roughly 5000 [35]. Experimental evidence confirms causal impacts: off-grid solar mini-grids increase household electrification by 29–36 percentage points relative to controls in rural India [38]. Across contexts, no included study reports a decline in electrification following mini-grid deployment.

Second, service availability and hours of supply are highly heterogeneous, and formal system availability often exceeds effective household access. Only nine studies report days-per-week availability numerically, most indicating nominal 7-day-per-week operation. However, hours-per-day metrics reported in 14 studies reveal sharp contrasts in service levels. At one end, several solar-hybrid and professionally managed systems provide continuous or near-continuous electricity (24 h/day) in the Philippines, India, and Nigeria [29,35,39]. At the other end, many systems deliver a constrained evening-only supply of approximately 4–5 h per day, notably in the Sundarbans [30], and in experimental DC micro-grids in India [38]. Severe supply limitations persist in some contexts: monitored data from southern Ethiopia indicate average load shedding of approximately 13 h per day, despite daily system operation [41]. These findings underscore that connection alone does not guarantee adequate electricity service.

Third, affordability outcomes are strongly context-dependent, shaped by technology choice, remoteness, tariff design, and subsidy regimes. Sixteen studies report affordability metrics explicitly. Many mini-grids reduce household energy expenditure relative to pre-electrification fuels, including kerosene and diesel generators. Tariffs range from very low-cost micro-hydropower systems (≈USD 0.02/kWh in Kenya) to high-cost solar systems in remote island settings (>EUR 1.30/kWh in Tanzania). Most contemporary solar-hybrid mini-grids cluster between USD 0.25 and 0.50/kWh, higher than subsidised national-grid tariffs but often associated with lower total household energy spending. Tiered tariffs, cross-subsidisation by productive users, and targeted subsidies improve affordability for low-consumption households, though long-term financial sustainability remains a recurring concern.

Fourth, reliability is widely discussed but unevenly measured. Only four studies explicitly report outage frequency or duration. Where quantified, reliability varies substantially: Daily outages are documented in Bulongwa, Tanzania (1–2 per day) [31], while southern Ethiopia exhibits prolonged daily interruptions driven by demand–capacity mismatch [41]. Several studies rely on categorical reliability bands or behavioural proxies, such as generator displacement, to infer service stability [36]. Evidence from portfolio-level analyses suggests that remote monitoring and professional operation can reduce downtime, though standardised outage metrics (e.g., SAIDI/SAIFI) are rarely reported.

Finally, consistency of supply (power quality) is the least documented energy metric. No included study reports standardised voltage/frequency statistics suitable for cross-study comparison. Where consistency is discussed, it is largely through qualitative accounts or proxy evidence (e.g., peak-demand stress windows), which limits comparability and reinforces the need for minimal power-quality reporting templates in future work.

These findings show that rural mini-grids reliably expand access and often improve service predictability relative to weak grids, but that service quality, affordability, and reliability remain highly variable. The literature is strongest on electrification and hours of supply, and weakest on power quality and standardised reliability measurement, pointing to clear priorities for future empirical research.

5.2. Future Research Directions

Despite important progress over two decades, significant research gaps remain. Most studies observe systems over short horizons, often within the first two years of operation. Multi-year monitoring and longitudinal designs are needed to capture demand growth, component degradation, tariff dynamics, and lifecycle performance. More rigorous counterfactual evaluation is also needed: only a small subset of studies employs experimental or quasi-experimental designs, while approaches such as regression discontinuity at electrification thresholds, synthetic controls, and instrumental-variable strategies remain underused in mini-grid contexts.

Service-quality measurement requires particular attention. Reliability reporting should move beyond perception-based proxies toward consistent outage metrics (frequency and duration), while power quality measurement should include standard voltage and frequency indicators as appliance loads and productive uses expand. Future research should also address distributional impacts more explicitly, including affordability burdens among the poorest households, gender-differentiated outcomes, and environmental sustainability issues such as battery end-of-life management and waste streams. Emerging technologies (e.g., second-life batteries and novel backup configurations) likewise require field-based evaluation using harmonised service-quality indicators.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/en19061441/s1.

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Data Availability Statement: The study-level extraction dataset supporting this review (indicator coding, bibliographic metadata, and quality-appraisal scores for the 22 included studies) is provided as Supplementary Material S1 (CSV).

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Table A1. PRISMA 2020 checklist.

Section/Topic	Item	PRISMA 2020 Checklist Item	Location in Manuscript
Title	1	Identify the report as a systematic review.	Title page
Abstract	2	Provide a structured summary in line with PRISMA 2020 for abstracts.	Abstract
Introduction	3	Describe the rationale for the review in the context of existing knowledge.	Section 1
Introduction	4	Provide an explicit statement of the objective(s) or question(s) the review addresses.	Research question and objectives
Methods	5	Specify inclusion and exclusion criteria and how studies were grouped for the syntheses.	Section 2.3 and Table 2
Methods	6	Specify all information sources (databases, registers, websites, organisations, reference lists) and date last searched.	Section 2.2 and (Table 1)
Methods	7	Present the full search strategies for all sources, including filters and limits used.	Section 2.2 and (Table 1)
Methods	8	Specify the methods used to decide whether a study met the inclusion criteria (screening).	Section 2.4 and Figure 1
Methods	9	Specify the methods used to collect data from reports, including any processes for obtaining/confirming data.	Section 2.5
Methods	10a	List and define all outcomes for which data were sought.	Section 2.5; Appendix B (Table A2)
Methods	10b	List and define other variables for which data were sought (e.g., study characteristics) and assumptions about missing data.	Section 2.5
Methods	11	Specify methods used to assess risk of bias/quality of included studies.	Sections 2.5 and 3.4; Appendix C (Table A3)
Methods	12	Specify effect measure(s) used for each outcome (if meta-analysis was planned).	Not applicable (no meta-analysis)
Methods	13a	Describe how studies were selected for each synthesis (if multiple syntheses).	Section 2.5; Section 3 (Results overview)
Methods	13b	Describe any methods used to prepare data for synthesis (handling missing data, conversions).	Section 2.5
Methods	13c	Describe methods used to tabulate or visually display results of individual studies and syntheses.	Section 3.2; Appendix B (Table A2); figure/table references
Methods	13d	Describe methods used to synthesise results and provide a rationale for choices.	Inserted paragraph in 2.5; 3.2
Methods	13e	Describe methods used to explore possible causes of heterogeneity.	Sections 3.4 and 4
Methods	13f	Describe any sensitivity analyses conducted.	Not conducted
Methods	14	Describe methods used to assess risk of bias due to missing results (reporting bias).	Not assessed (no meta-analysis); see Section 2.5
Methods	15	Describe methods used to assess certainty/confidence in the body of evidence.	Quality appraisal approach in Sections 2.5 and 3.4
Results	16a	Describe results of the search and selection process (numbers screened, assessed, included).	Section 2.4; Figure 1; abstract
Results	16b	Cite studies that might appear to meet criteria but were excluded, and explain why.	Figure 1 (reasons for exclusion)
Results	17	Cite each included study and present its characteristics.	Section 3.1; Appendix B (Table A2)
Results	18	Present assessments of risk of bias/quality for each included study.	Section 3.4; Appendix C (Table A3)
Results	19	For all outcomes, present summary statistics and effect estimates for each study, where available.	Sections 3.2.1–3.2.6
Results	20a	Summarise the characteristics and results of each synthesis.	Sections 3.2 and 3.4
Results	20b	Present results of all statistical syntheses (meta-analysis), if conducted.	Not applicable
Results	20c	Present results of investigations of heterogeneity, if conducted.	Qualitative heterogeneity discussed in Section 3.4

Table A1. *Cont.*

Section/Topic	Item	PRISMA 2020 Checklist Item	Location in Manuscript
Results	20d	Present results of sensitivity analyses, if conducted.	Not applicable
Results	21	Present assessments of reporting biases, if assessed.	Not applicable
Results	22	Present assessments of certainty/confidence in the evidence.	Section 3.4 (quality appraisal used as confidence lens)
Discussion	23a	Provide a general interpretation of results in the context of other evidence.	Section 4
Discussion	23b	Discuss limitations of the evidence included in the review.	Section 4 (limitations paragraphs)
Discussion	23c	Discuss the limitations of the review processes used.	Section 4 (limitations paragraphs)
Discussion	23d	Discuss implications of the results for practice, policy, and future research.	Sections 4.5, 5.1 and 5.2
Other information	24	Provide registration information for the review, and where the protocol can be accessed, or state not registered.	Section 2.1 (Protocol registration statement)
Other information	25	Describe sources of support and the role of funders.	Funding section
Other information	26	Declare any competing interests.	Conflicts of interest section
Other information	27	Report availability of data, code, and other materials.	Data availability statement; Appendix A

Appendix B

Table A2. Study-level mapping of reported energy-access service indicators (n = 22). This table records whether a study reports any evidence for an indicator; conceptual boundaries and harmonisation rules are provided in Table 4.

TI	PY	Electrification Rate	Availability of the Electricity Supply	Hours of Electricity Supply	Affordability of Electricity	Reliability of Electricity Supply	Consistency (Power Quality)
Assessing the Impact of Renewable Energy on Local Development and the Sustainable Development Goals: Insights From a Small Philippine Island	2020	Yes	Yes	Yes	Yes	No	No
Benefits and Challenges to Productive Use of Off-Grid Rural Electrification: The Case of Mini-Hydropower in Bulongwa, Tanzania	2019	Yes	Yes	Yes	Yes	Yes	No
Comparative Evaluation of Rural Electrification Project Plans: A Case Study in Mexico	2019	Yes	No	No	Yes	No	No
Does Basic Energy Access Generate Socioeconomic Benefits? A Field Experiment with Off-Grid Solar Power in India	2017	Yes	Yes	Yes	Yes	No	No
Empowering Low-Income Communities with Sustainable Decentralised Renewable Energy-Based Mini-Grids	2023	No	Yes	No	Yes	No	No
Energy Production Analysis and Optimisation of Mini-Grid in Remote Areas: The Case Study of Habaswein, Kenya	2017	Yes	Yes	No	Yes	No	No
Evaluating the Impact of Productive Uses of Electricity on Mini-Grid Bankability	2022	Yes	No	Yes	Yes	No	No

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Table A2. *Cont.*

TI	PY	Electrification Rate	Availability of the Electricity Supply	Hours of Electricity Supply	Affordability of Electricity	Reliability of Electricity Supply	Consistency (Power Quality)
Expanding Access to Clean Energy in Developing Countries: The Role of Off-grid Mini Hydro Power Projects in Kenya	2019	Yes	Yes	Yes	Yes	No	No
Factors Influencing the Sustainability of Micro-Hydro Schemes in Nepal	2021	No	No	Yes	No	No	No
Impacts of Electrification with Renewable Energies on Local Economies: The Case of India's Rural Areas	2014	Yes	No	Yes	Yes	No	No
Is Community Renewable Energy Always Just? Examining Energy Injustices and Inequalities in Rural Indonesia	2021	No	No	No	Yes	No	No
Pathways to Universal Electricity Access for Rural Communities in Africa	2020	No	No	No	Yes	No	No
Performance and Reliability Analysis of an Off-Grid PV Mini-Grid System in Rural Tropical Africa: A Case Study in Southern Ethiopia	2023	No	Yes	Yes	No	Yes	No
Rural Electrification in Africa: A Case Study of Yebu Community Solar Mini-Grid	2022	No	No	Yes	No	Yes	No
Social and Economic Impact Analysis of Solar Mini-Grids in Rural Africa: A Cohort Study from Kenya and Nigeria	2024	No	No	No	No	No	No
Socio-Economic Analysis of Solar Photovoltaic-Based Mini-Grids in Rural Communities: A Ugandan Case Study	2022	Yes	No	No	No	No	No
Socio-Economic Impacts and Challenges Associated With the Electrification of a Remote Area in Rural Tanzania Through a Mini-Grid System	2021	No	Yes	Yes	Yes	No	No
Socio-Economic Impacts of a Micro-Hydropower Plant on Rural Livelihoods	2011	No	No	No	Yes	No	No
Socio-Economic Impacts of Energy Access through Off-Grid Systems in Rural Communities: A Case Study of Southwest Nigeria	2022	No	No	No	Yes	No	No
Socio-Economic Impacts of Rural Electrification in Tanzania	2019	Yes	Yes	Yes	Yes	No	No
Solar Microgrids in Rural India: A Case Study of Household Benefits	2021	No	No	No	Yes	No	No
Sustainability of Community-Owned Mini-Grids: Evidence From India	2019	No	No	Yes	No	Yes	No

Appendix C

Table A3. Quality assessment results for included studies (*n* = 22).

TI	PY	Q1_Research Clarity	Q2_Study_ Design Relevance	Q3_Sampling Adequacy	Q4_Context Trans-parency	Q5_Outcome Validity	Q6_ Measurement Reliability (Data Source)	Q7_Bias/ Confounding Control	Q8_Analytical Rigour	Q9_Ethical and Funding Transparency	Q10_ Generalisability/ Transferability	Total Q1–Q10
Assessing the Impact of Renewable Energy on Local Development and the Sustainable Development Goals: Insights From a Small Philippine Island	2020	2	2	2	1	2	1	1	2	0	1	14
Benefits and Challenges to Productive Use of Off-Grid Rural Electrification: The Case of Mini-Hydropower in Bulongwa, Tanzania	2019	2	1	1	2	1	1	0	1	1	1	11
Comparative Evaluation of Rural Electrification Project Plans: A Case Study in Mexico	2019	2	1	1	2	1	1	0	2	1	2	13
Does Basic Energy Access Generate Socioeconomic Benefits? A Field Experiment with Off-Grid Solar Power in India	2017	2	0	2	1	1	2	2	2	2	1	15
Empowering Low-Income Communities with Sustainable Decentralised Renewable Energy-Based Mini-Grids	2023	2	1	1	1	1	1	0	1	1	1	10
Energy Production Analysis and Optimisation of Mini-Grid in Remote Areas: The Case Study of Habaswein, Kenya	2017	2	1	0	2	1	2	0	2	1	1	12
Evaluating the Impact of Productive Uses of Electricity on Mini-Grid Bankability	2022	2	1	1	2	2	2	1	2	1	2	16
Expanding Access to Clean Energy in Developing Countries: The Role of Off-grid Mini Hydro Power Projects in Kenya	2019	2	1	1	2	1	1	0	1	1	2	12
Factors Influencing the Sustainability of Micro-Hydro Schemes in Nepal	2021	2	1	1	2	1	1	0	1	1	2	12
Impacts of Electrification with Renewable Energies on Local Economies: The Case of India's Rural Areas	2014	2	1	1	1	1	2	1	2	1	2	14
Is Community renewable Energy Always Just? Examining Energy Injustices and Inequalities in Rural Indonesia	2021	2	1	1	2	0	1	0	2	1	2	12
Pathways to Universal Electricity Access for Rural Communities in Africa	2020	2	2	1	2	2	2	0	2	2	2	17

Table A3. *Cont.*

TI	PY	Q1_Research Clarity	Q2_Study_ Design Relevance	Q3_Sampling Adequacy	Q4_Context Trans- parency	Q5_Outcome Validity	Q6_ Measurement Reliability (Data Source)	Q7_Bias/ Confounding Control	Q8_Analytical Rigour	Q9_Ethical and Funding Transparency	Q10_ Generalisability/ Transferability	Total Q1–Q10
Performance and Reliability Analysis of an Off-Grid PV Mini-Grid System in Rural Tropical Africa: A Case Study in Southern Ethiopia	2023	2	2	1	2	2	2	1	2	1	2	17
Rural Electrification in Africa: A Case Study of Yebu Community Solar Mini-Grid	2022	2	2	1	2	1	1	0	1	1	2	13
Social and Economic Impact Analysis of Solar Mini-Grids in Rural Africa: A Cohort Study from Kenya and Nigeria	2024	2	2	2	2	1	1	1	2	2	2	17
Socio-Economic Analysis of Solar Photovoltaic-Based Mini-Grids in Rural Communities: A Ugandan Case Study	2022	2	2	1	2	1	1	0	1	1	2	13
Socio-Economic Impacts and Challenges Associated With the Electrification of a Remote Area in Rural Tanzania Through a Mini-Grid System	2021	2	2	1	2	1	1	0	1	2	1	13
Socio-Economic Impacts of a Micro-Hydropower Plant on Rural Livelihoods	2011	2	1	1	1	1	1	0	1	1	2	11
Socio-Economic Impacts of Energy Access through Off-Grid Systems in Rural Communities: A Case Study of Southwest Nigeria	2022	2	2	1	2	1	1	0	1	1	2	13
Socio-Economic Impacts of Rural Electrification in Tanzania	2019	2	1	1	1	1	1	0	1	1	2	11
Solar Microgrids in Rural India: A Case Study of Household Benefits	2021	2	2	1	2	1	1	0	1	1	2	13
Sustainability of Community-Owned Mini-Grids: Evidence from India	2019	2	2	1	2	1	1	0	2	2	2	15

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