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Review Article

Renewable Energy Systems in Supporting Climate Resilience of Off-grid Communities: A Review of the Literature and Practice

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ABSTRACT

Access to clean energy is a development imperative, particularly for the estimated 3.5 billion people globally residing in off-grid settings who lack reliable electricity access. As the energy sector faces increasing climate change impacts, and these communities emerge as particularly vulnerable, developing locally sourced, clean, and renewable energy systems becomes crucial for sustaining life on ancestral lands. While renewable energy systems can play essential roles in supporting sustainable livelihoods and building climate resilience in these communities, their successful implementation remains challenging. This paper presents the first bibliometric analysis of peer-reviewed literature, industry and government studies examining established foundations—including frameworks, models, theories, and concepts—relevant to community-scale infrastructure and natural resource management. Analysis of practical case studies from 37 countries reveals a significant gap in addressing socio-cultural dimensions, with only 30% of studies considering these factors in their examination of barriers and enablers, despite the dominance of socio-technical and socio-economic considerations. This global analysis establishes benchmarks for implementing renewable energy systems in off-grid communities. As the first stage of a doctoral research project, this review aims to identify empirically based approaches and develop context-specific, culturally appropriate strategies for implementing renewable energy systems that enhance community resilience to climate change.

KEYWORDS

Sustainable resilience of the system, renewable energy systems, socio-cultural dimensions, literature review, climate resilience, community.

INTRODUCTION

Access to clean energy is a development imperative, yet an estimated 3.5 billion people worldwide lack reliable and sustainable electricity access [1]. Among those affected, this challenge is most acute in remote and isolated settings that lie beyond the reach of national electrical networks, or what are referred to as off-grid areas. In these off-grid communities, a common pattern emerges: low population density, limited infrastructure, minimal economic activity, physical accessibility constraints, and significant distances from external markets

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collectively restrict access to essential goods and services [2], [3]. While they utilise stand-alone or distributed energy systems for power generation, these communities predominantly rely on fossil fuels like diesel and kerosene as their primary energy source [4]; driven largely by the relative ease of acquisition and installation. This dependence, however, exposes them to persistent challenges including price volatility, transportation difficulties, high operational and maintenance costs, and adverse environmental impacts [5]. Recent studies of coastal and island communities demonstrate that even with targeted renewable energy interventions, many communities struggle to achieve optimal sustainability performance, highlighting the complexity of energy transitions in isolated settings [6]

While some articles presented a review of renewable energy systems (RES) implementation in off-grid settings [5], [7], [8] current literature lacks a comprehensive systematic review that addresses three key aspects:

- the holistic integration of evidence beyond geographical boundaries (specific country/region), bridging insights from both developed and developing countries;
- the comprehensive incorporation of diverse geographical characteristics of off-grid communities; and
- the specific connection between RES implementation and community climate resilience.

This paper, representing the first stage of the doctoral research, analyses the foundations, barriers, and enablers influencing RES implementation, drawing practical evidence from 37 case studies. This review also integrates 11 foundational theoretical frameworks relevant to community-scale infrastructure and natural resource management, having correlation with renewable energy and climate change. These foundations—from Asset Based Community Development [9] to Decolonisation Theory [10], developed and used by both academia and practitioners, to explore enabling conditions that can enhance RES implementation's potential for strengthening community climate resilience in off-grid settings. By examining diverse theoretical perspectives and worldwide practical case studies, this review identifies key principles, barriers, and enablers to determine what is needed for future improvement. The insights gained will serve as the basis for developing a context-appropriate RES implementation guidance for climate-resilient off-grid communities, which is the aim of the whole doctoral research. This guidance will be further refined through detailed case studies in Indonesia and Australia in the next stage of this research.

METHODS

The methods section outlines the systematic approach undertaken for this study, including the scope and boundaries of RES reviewed. It details the search criteria and analytical frameworks employed, alongside an acknowledgment of the study's limitations.

Scope of the review and boundaries of the renewable energy system discussed

The review centers on RES, here defined as a combination of interdependent and interacting elements generating any form of energy, along with its co-benefits sourced from clean and renewable resources. Co-benefits for the purpose of this research are services in addition to power supply that a RES delivers without electricity being the prerequisite yielded from RES' multifunctionalities which the International Renewable Energy Agency (IRENA) named as "non-energy services" [11]. Water harvesting from hydropower dams and solar panel shading for farming activities are examples of non-energy services provided by RES. The primary function of RES is to not only support a community's basic infrastructure by supplying energy but also to support, through its co-benefits, community self-resilience and ease their vulnerabilities to climate change impacts. The term RES in this research is confined to the context outside the primary power grid, or can be referred to as an off-grid, mini-/micro-grid, distributed generation, or decentralised RES.

This research focuses on solar photovoltaic (PV), wind, and hydro energy generation, the most common energy sources found in off-grid communities, including small islands [4], [5]. These energy types deliver reliable electricity supplies, support many climate adaptation solutions, and vital community functions strongly linked with climate change resilience [12]. In the context of hydro, this study concentrates on micro- and mini-hydro, referred to as small-hydro projects (SHP). By focusing on solar PV, wind, and SHP, other renewable resources such as tidal, wave, ocean, biomass, biogas, geothermal, and municipal waste energy are excluded. This review only considers small-scale RES, which are referred to here as having a maximum capacity of around 10 Mega-Watt (MW), and a hybrid configuration with one of the three renewable types of hydro, PV, and wind energy with a diesel generator is also included in this analysis of RES case studies.

Search criteria and frameworks

This paper serves as a scoping study rather than involving primary research. It analyses published papers and reports to map the theoretical and practical foundations established in the context of renewable energy, climate change, and community resilience in off-grid, including remote and isolated areas. The study utilised databases such as Scopus, Web of Science, and Google Scholar to identify relevant literature. Additionally, grey literature, including government publications and organisational/industry reports, was selectively searched and analysed. The aim was to synthesise the critical principles for implementing RES to support climate-resilient communities in off-grid areas. The literature search for theoretical and practical foundations was not limited by time boundaries but was restricted to English-language publications.

The second stage of this literature review examined practical case studies for the barriers and enablers of RES implementation in off-grid communities, using the search criteria of: participants, interventions, comparison groups, and outcomes (PICO) framework [13], as shown in Table 1.

Table 1. Search strings using the PICO framework [13]

Elements	Search strings
Participants (P): Remote and Isolated Communities	“remote communities” OR “isolated communities” OR “small island communities” OR “rural communities” OR “coastal communities” OR “vulnerable communities” OR “SIDS” OR “low-middle income countries” OR “developing countries” OR “indigenous communities”
Intervention (I): Renewable Energy Systems (RES)	“renewable energy” OR “renewable energy technologies” OR “renewable energy systems” OR “low carbon energy technologies” OR “electrification” OR “mini-grid” OR “minigrid” OR “micro-grid” OR “microgrid” OR “off-grid” OR “offgrid” OR “solar photovoltaic” OR “solar PV” OR “micro-hydro” OR “microhydro” OR “mini-hydro” OR “minihydro” OR “small-hydro” OR “wind” OR “small-scale” OR “distributed generation” OR “decentrali* energy” OR “hybrid” OR “community energy”
Outcome (O): Climate Resilience	community resilience, community adaptation, climate adaptation, climate resilience, climate resilient development, community engagement, community participation, stakeholder engagement, participatory research, sustainable development, SDG, community empowerment

The PICO framework was used captures key searchable terms identified for a focused research question [14]. Detailed inclusion and exclusion criteria are presented in Table 2.

Table 2 Inclusion/ exclusion criteria using the PICO framework

Elements	Inclusion/ exclusion criteria
Participants/ population	- Include: focus on remote, isolated, and small islands communities - Exclude: urban
Intervention	- Include: focus on solar PV, small hydro, wind - Exclude: biogas, biomass, geothermal, ocean energy, utility-scale power plant, utility grid, Solar Home Systems
Comparison/ control	N/A
Outcome	- Include: discussed relevant factors influencing community adoption, acceptance, use, utilisation, consumption of energy generated from renewable energy technologies - Exclude: technical engineering solution-oriented; feasibility studies
Publication type	- Include: implied practical case studies; peer-reviewed and published journal articles, conference paper, book chapter, and grey literature; - Exclude: non-English literature, published before 2007

Our review examines real-world renewable energy implementation case studies from English-language literature published since 2007. The 15-year period represents a period according to IRENA when the cost of RES components decreased, indicating increased demand and significant technological advancement of RES between 2010-2020 [15]. Many of these practical case studies, while drawn from theoretical findings, were not focussing on theoretical outputs and were typically located in non-peer reviewed documents. Conversely, literature on theoretical insights were predominantly located in peer-reviewed journals where less practical approaches and outcomes were reported. This pattern justified our review's emphasis on integrating both theoretical and practical foundations.

In examining practical case studies identified, this paper used the conceptual framework introduced by Njoh (2021) [16], that focuses on seven dimensions of an environment or a system in a built environment to analyse the barriers and enablers of RES implementation in off-grid communities worldwide. The framework covers the political, economic, social, technological, ecological, cultural, and historical dimensions (PESTECH), providing a comprehensive analysis of a system and filling the gap of lack of socio-cultural context in current development and energy projects-related studies, compared to technological dimensions [17], [18]. PESTECH as a framework positions the social, cultural, and historical dimensions of a built environment systems to be equally essential as technological dimensions.

Limitations

The transdisciplinary nature of this research means a narrative literature review is a good fit to comprehensively establish the knowledge available at a particular point of time and in a particular field and emphasise the significance new area of research [19]. However, comprehensive and broader coverage of narrative literature review has its trade-off of being a less transparent method compared to systematic review [20]. Although narrative reviews are evidence-based, they can be prone to selection bias due to the lack of explicit selection criteria [21]. To address these limitations, this review incorporates systematic elements: stating clear review aims, establishing a clear scope and explicit literature inclusion and exclusion criteria (particularly for case studies), conducting comprehensive literature searches following the PICO framework, and assessing the quality of included literature to ensure both established foundations and practical case studies were sourced from credible global institutions.

RENEWABLE ENERGY FOR CLIMATE RESILIENT OFF-GRID COMMUNITIES: A REVIEW OF THEORETICAL AND PRACTICAL FOUNDATIONS

This section examines community climate resilience frameworks and identifies key principles for implementing renewable energy systems in off-grid communities to enhance their climate resilience based on established theories and approaches.

Definition of climate resilient communities

There is little consensus about the definition of climate resilience. The Intergovernmental Panel on Climate Change (IPCC) describes it as: *"the ability of a system and its components to anticipate, absorb, accommodate, or recover from the effects of a hazardous event in a timely and efficient manner"* [22]. As resilience in the context of climate change is an interrelated concept with vulnerability, exposure, and risks, adaptation is frequently set around resilience, which entails the ability to recover and revert to a former state (essential function, identity, and structure), and also the potential for transformation following a disruption [23]. This correlation aligns with how the International Federation of Red Cross and Red Crescent Societies (IFRC) refers to resilience, as *"a process of adaptation before, during, and after an adverse event"* [24]. By combining the definition of renewable energy by IRENA and of climate resilience by IPCC, RES in this paper is defined not solely as renewable energy uptake for power but rather as a system delivering energy-powered services, such as household electrification, public health, education, business, and emergency disaster response, alongside non-energy services that support the community's capability in anticipating, coping with, and recovering from any shocks, disturbances, or losses triggered by climate change impacts. Figure 1 illustrates the fundamental elements of constructing climate resilience of off-grid communities as presented in this paper.

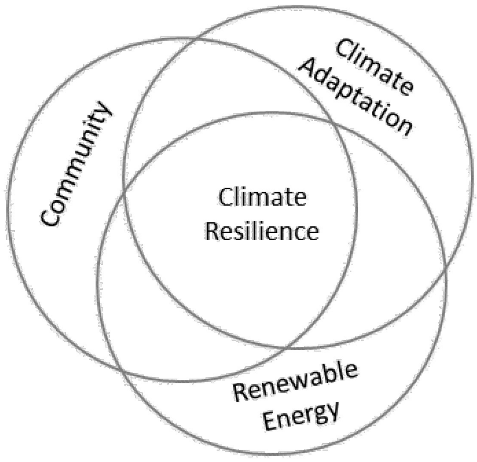

Figure 1 Fundamental elements of constructing climate resilience of off-grid communities

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Theoretical and practical foundations for implementing renewable energy systems

The purpose of this literature review was to develop a guidance to offer empirically based approaches for implementing RES in off-grid community settings, based on best practices, and that address the shortcomings of those practices developed and used to date. That is, a set of foundations were identified from different scholarly disciplines that revolve around community-scale infrastructure and resource management and included the following eleven foundations relevant to community-scale infrastructure and resource management.

These eleven foundations prioritise the application of community-based approaches and emphasise the non-technical dimensions of community-scale infrastructure and natural resource management. The eleven foundations were sourced from peer-reviewed journals or endorsed by credible global organisations such as the IPCC, United Kingdom Department of International Development (DFID), International Institute for Environment and Development (IIED), and IFRC:

- Asset Based Community Development (ABCD)
- Sustainable Livelihood Approach (SLA)
- Community Capital Framework (CCF)
- Socio-Ecological System Framework (SESF)
- Community-based Adaptation (CBA)
- Climate Resilient Development (CRD)
- Framework for Community Resilience (FCR)
- Common Pool Resources (CPR)
- Polycentric Governance
- Community Energy
- Decolonisation Theory

The foundations and their principles are presented in Table 3. While eleven foundations are included in this paper, other foundations that put community at the centre of community-scale infrastructures and resource management were considered for analysis, including: Hyogo Framework for Action [25]; co-designed, refined, and collaborated frameworks such as Socio-Technical Energy Transition [26]; Three Pillar/Integrated Forest Landscape Management Framework [27]; and Transformative Community Water Governance [28]. They were excluded from the review because they were either in different areas of expertise such as disaster, water, or forest management, or did not align with the research outcomes this paper contributes to. This exclusion was despite some of the frameworks being based on similar key principles of bottom up and people-centred approaches.

Table 3 Overview of eleven theoretical and practical foundations reviewed in this paper

No	Existing Foundation	Purpose, developer(s)	Short Description	Key Principles/Elements	References
1	ABCD	Academic: Kretzmann & McKnight (1993)	For sustainable community driven development building on strengths and capacities of community members, internal associations, and institutions in the community.	- Strength- and asset-based - Community led - Connectivity oriented - Participatory, inclusion focused	[9], [29], [30], [31], [32]
2	SLA	Practice: DFID (1999)	Regards livelihoods as inclusive of the resources, abilities, and actions required for survival and living. Attempts to enable deeper understanding of the vulnerability context focusing on five assets or capitals of households, namely, physical, natural, human, social, and financial.	- People centred, with people's social and economic activities at the centre of the analysis - Consider interventions with transcend sectoral boundaries - Responsive and participatory - Focus on strength/ existing resources or capitals - Emphasises participatory process and being responsive - Broad view of sustainability from the five capitals	[33], [34]
3	CCF	Academic: Flora & Flora (2004)	Offers new perspectives on long-term well-being and sustainability of communities through their seven capitals: cultural, human, social, political (human – intangible), natural, financial, and built (material – tangible). Attempts to identify and comprehend these resources, their	Similar to SLA's key principles, with following differences: - Concentrated on political and cultural capitals, in addition to SLA's five focused assets - Enables vision to work with community resources, not only	[34], [35], [36]

			interactions, and how they collectively influence community functioning. Assesses the value and impact of specific interventions aimed at community development.	individual/ family resources, across the seven capitals	
4	SESF	Academic: Berkes, Folke, & Colding (1998, 2000); Anderies, Janssen, & Ostrom (2004); Ostrom (2007, 2009)	Investigates the interactions between the governance of biological basis of ecosystems (recently used also for humanly designed technological systems, such as energy infrastructure) and social processes. Focuses on "actor situation" where multiple actors interact with each other under the influence of different contextual variables, such as resource systems, resource units, governance systems, actors.	- Maintains diversity and redundancy of species, landscape types, actors, and institutions - Manages connectivity of resources, species, and people - Manages slow variables and feedback - Fosters complex adaptive systems (CAS) thinking - Encourages learning by acquiring new information, skills or understanding - Broadens participation by active engagement of stakeholders in projects - Promotes polycentric governance systems	[37], [38], [39], [40]
5	CBA	Practice: IIED (2005)	Focuses explicitly on most-vulnerable to climate change communities and highlights community-led process, based on community priorities, needs, knowledge, and capacities, which should empower people to plan for and cope with the impacts of climate change.	- Community-driven (bottom up and participatory approach) - Vulnerability-led - Strength-based - Place-based - locally appropriate solutions/ strategies emerged from integration of local and scientific knowledge - Possibility to scale up and scale out	[41], [42], [43]
6	CRD	Practice: IPCC (2014)	Combines strategies to adapt to climate change with actions to reduce greenhouse	- Ecosystem stewardship	[23], [44], [45], [46]

			gas emissions to support sustainable development for everyone.	- Equity and justice - Inclusion - Knowledge diversity	
7	FCR	Practice: IFRC (2008; 2014)	Conceptualises resilience at multiple levels, individual and household level to national governments and whole geographic regions, through these objectives: assisting communities with risk-informed approaches, promoting people-centered resilience strengthening, and ensuring universal connectivity to prevent human suffering. Refined from previous IFRC Community Safety and Resilience Framework.	- Assists communities to adopt risk-informed, holistic approaches to address underlying vulnerabilities - Demand driven, people-centred - Connected to communities	[24], [47]
8	CPR	Academic: Ostrom (1990)	Refers to '*A natural or man-made resource* system *that is sufficiently large as to make it costly (but not impossible) to exclude potential beneficiaries from obtaining benefits from its use'*. Attempts to explain how social institutions can form and achieve sustainable management of common pool resources (non-excludable, but rivalrous in consumption) through 8 principles.	- Clearly defined boundaries - Proportional equivalence between benefits and costs - Collective-choice arrangement - Development of a monitoring system - Application of graduated sanctions - Conflict-resolution mechanism - Minimal recognition of rights to organise - Nested enterprises	[48], [49], [50], [51], [52]
9	Polycentric Governance	Academic: Ostrom, Tiebout and Warren (1961)	System of governance in which many centres of decision-making authority are needed to cover the full range of governance tasks, emphasising decentralisation, local embedding, and responsiveness to specific contextual conditions.	- Self-organisation (agents organise among themselves at the local scale) - Governing units collaborate - Attitude of learning is in place - Overarching rules and boundaries target the functioning initiatives - Architecture for fair and efficient conflict resolution is in place	[53], [54], [55]

10	CE	Academic: Walker & Devine-Wright, 2008; Practice: European Commission, adopted in 2019	Community energy or energy community referred to as energy initiatives that prioritise the active involvement of local community members in terms of ownership and decision-making. European Commission specifically defines a typology of CE, the Community Renewable Energy (CRE) that is strongly tied to a specific geographical location, thereby establishing a close association between the community and the local energy source.	- Democratic control - Sharing benefits - Active participation - Sustainability and scale of technology choices	[56], [57], [58], [59], [60]
11	DT	Academic & practice Developed by decolonisation scholars and activists since mid-20th century, one of which is Linda Tuhiwai Smith for the expansion in multidisciplinary contexts in 1999	Decolonisation theory is fundamentally about shifting top-down paradigms in favor of empowering local and Indigenous voices. Integrating decolonisation theory is crucial for examining diverse knowledge systems and developing solutions to complex socio-environmental challenges that transcend one-size-fits-all approach.	- Challenging power dynamics - Recognition of indigenous knowledge - Self-determination and autonomy - Context-specific solutions - Equity and justice	[10], [61], [62]

Principles and elements for successful renewable energy systems implementation

IFRC defines a community as "*a group of people who may or may not live within the same area, village or neighbourhood, share a similar culture, habits and resources, also exposed to the same threats and risks such as disease, political and economic issues and natural disasters*" [24]. Development resilient communities means defining the term resilience, which Kais and Islam (2016) propose as being the dynamic elements of: threat–general or specific resilience; systems–hard, mixed, or soft; and response–resistance and maintenance, change at the margins, and openness and adaptability [63]. Climate resilience in this paper therefore can refer to a soft system and specific resilience, focusing on the adaptive capacity of a community in response to a particular threat, in this context, climate change impacts. Elmqvist *et al.* (2019) highlighted that climate resilience could be translated into social, community, technological infrastructure, or ecological resilience, depending on the different elements impacting the resilience level of a general system [64]. Similarly, the desired climate resilience outcome, potentially achieved through a better approach for RES applications, resonated with Handmer and Dovers (1996) who argued that "openness and adaptability", is the level of resilience that goes beyond addressing surface symptoms and therefore demands fundamental and necessary changes [65].

Further, a 'climate-resilient community' can be defined as a group of people with the above characteristics (i.e. they possesses a set of adequate assets and resources) to enhance its capacity to adapt to, and cope with, long-term shifts triggered by climate change impacts [63]. Beyond that, community resilience needs to be re-framed as being more than sustaining status quo and bouncing back after disturbance, but instead being prepared and intriguing to possible transformations triggered by environmental and social issues demanded to address [66].

Drawing from the key principles of each theoretical and practical foundation reviewed, relevant fundamental principles that might be instrumental for implementing RES in off-grid communities to achieve the desired climate resilience goal were derived. A coverage of synthesised elements across different theoretical and practical foundations discussed in this paper is presented in Table 4.

Table 4 The coverage of synthesised elements across different eleven theoretical and practical foundations discussed in this paper

Key principles	Theoretical and practical foundations									
	A	B	C	D	E	F	G	H	I	J	K
People-centred approach	√	√	√		√		√			√	√
Inclusive, participatory process	√	√	√	√		√	√	√	√	√	√
Assets/ resources/ strengths recognition and mobilisations	√	√	√	√	√	√				√	√
Place-based; culturally appropriate; and communities' vulnerabilities reduction-focused solutions			√		√		√		√	√	√
Mutual learning and transparent information dissemination			√	√		√			√		√

Multi-stakeholder involvement and shared responsibilities				√		√	√	√	√	√	
Strong governance and monitoring				√				√	√	√	

A: ABCD, B: SLA, C: CCF, D: SESF, E: CBA, F: CRD, G: FCR, H: CPR, I: Polycentric Governance, J: CE, K: DT

People-centred approach. Asset-driven or needs/demand-driven, intervention objectives and priorities must have the people involved at the beginning. Bottom-up, community-led, where the communities are involved, active and responsive, including in decision making and problem-solving process. Aim for community empowerment and knowledge level raising through multiple approaches and directly counter colonial model that disregard local input when impose external solutions.

Inclusive, participatory process. Inclusion-focused emphasises local community engagement as a citizen. Inclusion vulnerable and underrepresented community members throughout the development process, addressing systemic marginalisation and power imbalances. Effective planning combines knowledge and value for resources for long-term community benefits.

Assets/ resources/ strengths recognition and mobilisation. Assets/ resources/ strengths within a community are well identified and mapped, including indigenous and local knowledge systems. Power of relationships and links within the community are thoroughly assessed, including at individual level. Use existing assets is encouraged as an "investment" to create more resources.

Place-based, locally and culturally appropriate, and community vulnerabilities reduction-focused solutions. Locally available sources are prioritised. Specific community vulnerabilities, risks, barriers in a defined location are understood and targeted. Local/ indigenous knowledge and traditional ecological practices incorporated as integral part of technological solutions, challenging the dominance of external or "universal" approaches. Respect placed on community's cultural heritage. Aim is for actions to reduce community vulnerabilities.

Mutual learning and transparent information sharing. Mutual, two-way learning for both local community and external actors to acquire new information, skills, or knowledge, and for developers/ outsiders to meaningfully integrate local knowledge into the program/ project/ intervention planning and implementation. Effective and well-designed information dissemination is transparent for entire project cycle: consultation, vision and goal setting, decision making, contribution in project deployment, and evaluation.

Multi-stakeholder involvement and shared responsibilities. Collaborative partnerships and improving capacity of people to collaborate for common objectives are encouraged. Non-technical experts involved from project inception. Capability to identify actors within and outside community. Capability to connect with external supports when necessary. Roles and responsibilities for each stakeholder involved are defined.

Strong governance and monitoring. Robust governance structures and clear ownership of the asset management. Strong leadership with strong commitment for transition and transformation. Established mechanisms for conflict management and resolutions. Institutional, social, and technical capacities developed for monitoring and evaluation.

BARRIERS AND ENABLERS OF RENEWABLE ENERGY SYSTEMS IN OFF-GRID COMMUNITIES: IDENTIFICATION FROM PRACTICAL CASE STUDIES

While many studies have evaluated the techno-economic feasibility of renewable energy generation in non-urban areas, this literature review draws on practical case studies from across the globe to identify the evidence-based barriers and enablers of RES practices in diverse off-grid communities with baseline studies or project evaluation reports. Practical case studies reviewed included mini-grid solar PV, hydro, and wind energy, or hybrid configuration of diesel generator with one of these three renewable energy sources. Stand-alone systems such as solar home systems (SHS) case studies are not considered in this analysis based on the inability of home systems to be integrated into a larger grid when electricity demand grows, local economic growth improved, or the national grid expands [67].

Selection of case studies

The case studies examined in this review are from low- and middle-income countries with significant electricity access issues, such as Asia-Pacific region including South Asia, Southeast Asia, and Pacific Small Island Developing States (13 cases), Africa region (10 cases), and Latin America and Caribbean (9 cases). This review also includes remote and indigenous communities in developed nations, such Australia, Canada, United States, European countries (5 cases) (Figure 2).

Figure 2 Distribution map of various case studies included in this review

Most of the cases were selected from single projects, but the post-implementation of multiple projects at program-level were reviewed, such as the: Chile Rural Electrification program; Australia Bushlight projects; Indonesia's government-funded microgrid projects; community-based solar PV projects in Malawi; and the Western China Rural Electrification program. Appendix 1 presents the practical case studies selected from a total of 37 countries reviewed.

Identified barriers and enablers

The analysis examines evidence-based barriers and enablers to RES implementation through the seven factors of PESTECH framework. The geographical barriers, frequently encountered as one of the main challenges in developing infrastructure for off-grid communities, are identified. This analysis also includes institutional barriers, a prevalent challenge in RES government-driven programs. Following Sietz et al.'s (2011) three-level distinction of institutional barriers [68], organisational and enabling environment barriers are addressed under "Political and Institutional" dimensions, while individual-level barriers (attitudes, knowledge, skills, personality traits, and beliefs) are examined within the "Social" dimension in this review. A summary of the key barriers and enablers is provided in Table 5.

Political and Institutional. Governance challenges in RES implementation manifest through both institutional and political dimensions. At the institutional level, barriers include non-transparent transfers from national to sub-national governments in Indonesia [54] and unclear post-construction ownership, as observed in Chile [69], Western China [70], and African mini-grid projects [71], [72]. Institutional barriers also stem from inadequate full-cycle project planning [73], [74], particularly post-implementation phase [70], including maintenance planning [75]. Political barriers compound these through heavily top-down approach from centralised governance with limited sub-national involvement [54], [76] and lack of long-term vision for energy transition from authorities [76]. Additional barriers include inconsistent regulations, administrative complexities, corruption tendencies, and non-transparent procurement frameworks [76], [77]. Political discontinuity, particularly evidenced in Nigerian projects, often disrupts implementation when new administrations change priorities [71].

However, several success enablers have been identified, including community ownership models as seen in India [78], and clear management structures in Malawi [72] and Zambia [79]. Strong intermediaries have also proven crucial, as demonstrated by IBEKA in Indonesia [77] and OLADE in Latin America [80], and catholic missionaries in Venezuela [81]. These intermediaries can facilitate communities' access to after-sale services such as warranty [79], supporting their operation and maintenance (O&M) activities. The establishment of community-driven organisations, rooted in the community's determination and collective action, has emerged as another key factor [82], [83], [84], particularly in developing mutual agreements and operational protocols [80]. Additional enabling factors include effective policy incentives [77], sustained sub-national support for communities during post-implementation phase [69], and high-level leadership commitment, especially in cases where renewable power implementation initially appeared unfeasible due to remote locations [82].

Multi-stakeholder partnerships at every stage of decision-making and implementation [54], [85] emerge as a crucial factor, particularly collaboration with local utilities as demonstrated in Guinea Bissau's Bambadinca [86] and Haiti's Les Anglais [80]. The integrated social relations of communities prove essential for asset sustainability, extending to micro-enterprise development, resident capacity building, and active community participation [87]. These elements work together to address operational challenges at the community level a lack of clear management structure and dedicated project personnel in place, especially key management positions [72], [79], leading to sustainable models that overcome financial and governance issues [78].

Strategic approaches further strengthen implementation through evidence-based decision-making, demonstrated by comprehensive cost-benefit analyses and capacity building of national and local authority knowledge on RES, putting them as the country's focal point as in Gambia case study [86]. Successful examples include Alaska's renewable-diesel hybrid model with minimal fossil fuel subsidies [88], and integration with national development priorities as shown in Cambodia [84], Philippines [89], and Bhutan [90]. These successes are underpinned by positive relationships across government levels and local communities [87], [91], highlighting how aligned governance structures at both institutional and political levels can enhance RES implementation outcomes.

Economic. Economic barriers to RES implementation manifest at both project and community levels. At the project level, challenges include higher levelised cost of energy (LCOE) an inability to address an optimal energy mix by prioritising locally available resources, as seen in Lucingweni, South Africa [73]. Dependency on limited financing sources like donor agencies [74], [77] and inadequate tariff structures since project inception evidenced in Fiji's failed renewable-hybrid micro-grid projects [92] can also impact in sustaining the operation of RES. These issues compromise O&M budgets including hardware replacement, hindering revenue generation, which then impact ongoing operational costs [69], [71], [74], [77]. Overall country economic instability can also have an influence [69]. At the community level, barriers can arise from low community willingness to pay for an electricity service [93]. Other economic barriers are exemplified in cases like Batzchocolá Village in Guatemala [80] where extreme poverty limits service affordability, and Mombou, Chad [86] where inaccurate purchasing power assessment alongside limited income-generating activities resulted in insufficient maintenance cost coverage. These factors collectively impact timely payment capabilities and system sustainability.

However, several economic factors enable successful RES implementation. The urgent need to reduce costly fossil fuel dependence in remote areas, particularly in indigenous communities like Pelelu Tepu (Suriname) [94], Fort Chipewyan (Canada) [82], and Alaska's remote villages [88], has driven the transition to cleaner, locally available energy source options. Other economic factors contributing to RES' success are government subsidies, exemplified by Nepal's successful rural electrification program with 250 SHPs [91]; financial incentives such as Scotland's Renewable Obligation Certification in the Isle of Eigg [83]; and multiple revenue stream resulting from business diversification in Latin America and the Caribbean [80]. Other case studies also showed that cost-sharing and blended financing facilitated through partnerships with various actors and institutions effectively reduce high investment costs of renewable-based off-grid leading to successful implementation [80], [84], [95]. Overall, financial self-sufficiency from adequate revenue generation and appropriate tariff design are the economic drivers to ensure sustainability [96].

Additionally, community-level success is demonstrated through reduced household expenditure as documented in the Dominican Republic [80], Haiti [97], Cape Verde [98], and the Philippines [95]. Moreover, in some cases, the benefits extend beyond electricity expenditure reduction to include successful productive use of energy (PUE) applications, as seen in Guyanan communities (Powiakuru, Kangaruma, and Shulinab) using solar PV systems with centralised storage for processing fish and wild meat [80], local entrepreneur growth in Gbamu village of Nigeria [99], and the French Island of La Réunion's solar PV for agricultural activities [100], [101]. Furthermore, the presence of RES also contributes to increased household income, particularly in above-average income households [89]. The combination of these entrepreneurship opportunities, job creation [82], and service affordability, balanced with communities' ability willingness to pay [87], [95], further contributes to sustainable implementation of RES in difficult-to-reach areas.

Social. Social barriers significantly impact RES implementation success in rural communities. Studies from Chile [69] and Malawi [72] reveal that limited community engagement from project inception often leads to project stagnation. In this case, rather than fostering active participation, engagement was often reduced to mere information provision, a pattern also observed in Nigerian communities [71]. The Chilean case further demonstrated how inadequate engagement models fail to address diverse community needs, while system failures can create negative perceptions that spread to other communities, exacerbating barriers to adoption. Meanwhile, the Nigerian case further highlighted insufficient grassroots capacity building and knowledge transfer, challenges similarly documented in Vanatu's Tanna Island [74], alongside the challenge of retaining skilled local operators and technicians particularly when some of the best local talent migrates for better opportunities, given the remoteness of their homeland [91]. Social tensions arising from land acquisition processes can further impede RES development [102].

Conversely, successful RES implementation is driven by strong social factors, particularly synergistic multi-stakeholder participation [80]. Trust-based schemes and mutual learning have proven effective in El Hierro, Spain [103] and Hispaniola Island, Dominican Republic [97]. The involvement of non-technical experts (anthropologists, sociologists, legal specialists) from project inception enhances community communication [67], resulting in high community awareness, significant local influence in decision-making processes and approval of project rules and measures [80], [83]. Active community participation will lead to other benefits, including contributions of labour during construction processes, land provision, and seeking financial sources at the construction stage [77], [80], also prevention of the asset vandalism during the operational stage [79].

Strong community leadership [77], [83] and women's group participation, as demonstrated in El Espino, El Carmen, and Itayovai mini-grids (Bolivia) [80] and Pelelu Tepu (Suriname) [94], significantly contribute to success. Communities that can assess needs, set priorities, and collectively decide on their future as both individuals and an organised group are likely to strongly drive the project to success [97]. This empowerment strengthened through comprehensive capacity building [104] and strategic engagement of community agencies, including youth in environmental awareness [69], [82] and religious institutions in electrification missions [81]. Knowledge transfer from external developers, scientists, and practitioners to local actors, generate valuable community skills [104], encompassing both technical expertise for power plant operations and maintenance, as well as essential managerial, business development, and financial management capabilities [85]. The broader benefits that communities directly experience from electricity access–including improved healthcare, education, emergency response, and overall livelihood–can serve as social drivers that collectively sustain successful RES implementation [80], [89], [94], [97].

<u>Technological.</u> Feron et al. (2016) [69] and Akinyele et al. (2018) [71] identified similar technical barriers to RES implementation emerge across three critical project phases. In pre-construction, inadequate surveys and poor system sizing lead to unrealistic power supply estimates while construction phase challenges include substandard installation quality and unqualified personnel. Additionally, post-construction issues center on operational challenges due to unreliability of system performance during operation due to a lack of compliance standards, absence of maintenance procedures and practices, lack of monitoring systems, and unavailability of spare parts locally. These operational challenges are particularly evident in remote areas, with limited technical expertise forcing reliance on external support, as seen in Fiji [92] and Vanuatu [74]. Additional challenges include overutilisation issues, demonstrated in Mpanta, Zambia [79] and Ghanaian rural islands [102], while Nepal's SHP cases highlight how early-stage design and installation issues can threaten long-term sustainability [91].

In contrast, robust technical enablers, starting with accurate resource mapping and future-ready system design, can lead to successful RES implementation [87], [96]. Examples include smart metering in Haiti and remote monitoring in Colombia's La Guajira [80], along with hybrid systems in Philippines' Cobrador Island [95] and appropriate technology adaptation like Peru's low-speed wind turbines [87]. Local resource factors, including spare parts availability [69], local service partnerships [91], and supporting infrastructure as seen in Caribbean microgrids [80], further enhance system sustainability. Comprehensive community training in both demand management and efficient use of electricity [81], [83], [96], [105], as well as technical O&M for local technicians [77], [84], [90], [95] has proven crucial for long-term success. For some off-grid RES cases, the prospect of future grid connection should be kept open for sustainability purposes [77].

<u>Ecological.</u> Ecological barriers significantly affect RES operations in remote areas, particularly for wind, hydro, and solar energy systems. Resource scarcity and seasonal variations [76] directly impact energy production, as demonstrated by the Zimbabwe's

Chipendeke SHP project, where decreased precipitation and drought reduced river flow and power generation capacity [106]. Additional challenges include natural phenomena like lightning strikes [81] and disaster events such as landslides and monsoons that can damage infrastructure [91].

Successful RES implementation, however, builds on several ecological enablers. The foundation begins with available local energy resources [93] and comprehensive climate datasets [85], including seasonal variations in hydrological parameters, wind patterns, and solar irradiance. The environmental benefits of RES can themselves become drivers, as seen in the Dominican Republic where communities engaged in reforestation to protect their SHP water resources [97]. Reducing a community's heavy reliance on forests through RES implementation, specifically communities which use fuelwood as the primary energy source for activities like cooking, can be a driver too [90]. Furthermore, RES adoption has proven particularly valuable in reducing fossil fuel dependency and enhancing resilience during extreme weather conditions, as demonstrated in indigenous communities of Fort Chipewyan (Canada) [82] and Crile Creek (Australia) [107], hard-to-reach area like Kaur (Gambia) [86], and the storm-prone El Hierro Islands [103].

<ins>Cultural.</ins> Cultural factors, often overlooked in project planning, play a crucial role in RES implementation success in off-grid areas. The South Africa's Lucingweni mini-grid case study demonstrated how limited understanding of local conditions by project partners led to operational challenges and potentially project failure [93]. Additional barriers emerged in Ghana's mini-grid deployment, where despite World Bank support, insufficient attention to local cultural dynamics created community-level challenges arising from socio-cultural behaviour within the community [102]. Language barriers further complicate implementation, as seen in Mongolian mini-grid projects, where technical documentation in foreign languages hindered effective O&M [108].

However, successful RES projects effectively leverage cultural enablers, particularly through integration of indigenous traditions and local knowledge. This is exemplified in Indonesia's Ciptagelar community, where traditional values about nature connection support project success [104], and in Bhutan's Sengor SHP, where Buddhist cultural identity and environmental conservation contribute to the country's carbon-negative status [109]. The significance of communal work spirit and collective values has proven crucial for successful implementation, demonstrating how cultural alignment can enhance project sustainability, as argued by Guerreiro and Botetzagias (2018) [77] and Njoh *et al.* (2022) [76].

<ins>Historical.</ins> Historical barriers, though less discussed can be contributing factors to the low acceptance rate or even failure of RES projects in off-grid communities. For example, a historical issue relates to instances where community members have previously experienced extended periods of free electricity access, leaving them unprepared for the transition to a paid electricity system [93]. This lack of preparation can lead to resistance and difficulties in introducing sustainable renewable energy solutions within these remote communities.

Conversely, historical drivers can positively influence community-driven initiatives. A case study in Cameroon [76] highlighted two such factors: the deep-rooted tradition of self-help and volunteerism, and the alignment of technological solutions with historical community practices, such as African communities' longstanding use of solar energy for food preservation and heating. Similarly, remote Alaskan communities demonstrate how historical resilience can enable RES adoption. Their ancestral survival in one of the world's most environmentally challenging regions has fostered what is known as a "culture of innovation" [88]. This heritage, combined with their traditional wisdom and cultural practices, has led Alaskan residents to approach local energy initiatives with enthusiasm and community pride, facilitating successful microgrid implementations.

Geographical. Geographical barriers are inherent in off-grid RES projects, particularly in areas unreachable by national grids. In geopolitically conflicted regions, such as the Esaghem solar PV mini-grid in Cameroon [76] and Chad's mini-grid projects [86], security issues disrupt maintenance schedules and logistics. Similarly, projects in disaster-prone areas face risks from flooding, earthquakes, and landslides, especially affecting site-specific installations like wind and SHP [85]. These environmental challenges can cause construction delays, cost overruns, and operational shutdowns, particularly for SHP projects requiring extensive civil work.

Regions with dispersed settlements and rough terrains present additional challenges for RES implementation [93], as low population density and scattered households make electricity network deployment costly. Limited accessibility impacts technical reliability by hampering repair and hardware replacement efforts [92]. Furthermore, for RES implementation linked with PUE, hard-to-reach locations can diminish the economic viability of the project. This is because such locations may restrict access to markets for PUE products, hindering the potential increase in local economic growth [91]. Geographical challenges are amplified in harsh environments, as demonstrated by Mongolian renewable-based mini-grid systems [108], where extreme conditions necessitate more sophisticated system deployment, increased maintenance efforts, and specialised component selection.

Table 5. Summary of identified barriers and drivers/enablers of RES practices derived from practical case studies

Dimensions	Barriers	Enablers
Institutional	- Improper project cycle planning - Long process, delay, lack of transparency in asset transfer process - Unclear ownership structure during operational phase - Lack of dedicated project personnel	- Multi-stakeholder engagement - Strong intermediary organisation - Clear management structure - Local organisation establishment - Partnership with local utilities - Development of appropriate management model taking into account social relations of community
Political	- Inadequate long-term vision - Vague, inconsistent, and contradictory RE policies - Bureaucratic complexities - Tendency for corruption - Limited sub-national government involvement - Political changes (ie. government structures) - Lack of transparency in procurement process	- Strong political commitment - Enabling legal framework - Leader's understanding of RE benefits - Positive government-community relations - Alignment with national priorities -
Economic	- Lack of long-term financial support - Country's economic instability - High upfront investment cost - Insufficient tariff mechanism	- Urgency to move away from heavy reliance on fossil fuels - Innovative financing mechanism

	- Unstable and low community income - Limited willingness to pay - High electricity tariff - Lack attention/planning for O&M and hardware replacement budget allocation - Inability of installed power plants to trigger income generating activities	- Government incentives/subsidies - Cost-effective technologies - Appropriate tariff design - Income-generating activities support - Availability and access to various funding, especially dedicated to post-construction stage
Social	- Poor community engagement - Lack of engagement models - Shortage of local skilled workers - Land acquisition issues - Negative perception towards relatively new technology - Absence of grassroot capacity building - Limited energy awareness	- Strong community participation - Effective community leadership - Local skill development - Local job creation - Inclusive stakeholder involvement - Community empowerment and ability to assess needs, set priorities, and make decisions - Involvement of religious institutions, younger population, and women - Contribution to improvement of community livelihood, public services, and security and safety
Technological	- Unrealistic estimation of power supply - Poor design/system sizing - Inadequate installation quality - Limited maintenance support - Unreliable performance - Overutilisation of electricity - Illegal connections - Absence of maintenance procedures and practices and monitoring systems - Limited troubleshooting capability	- Proven, appropriately selected, socially fitted technology - Accurate and realistic estimation of energy resources and demands - Robust design and configuration and supporting system performance - Easy access to spare parts and long-term post-construction services - Service reliability and community satisfaction - Active participation of community on demand management - Future grid connection options - Trained local resources for O&M

Ecological	- Resource scarcity - Weather dependence - Natural hazards - Infrastructure damage risks	- Local resources availability - Sufficient data for related variables and parameters - Ecological assessment - Biodiversity protection - Community resilience measures
Cultural	- Limited understanding of local traditions - Conflicting development views - Language barrier	- Indigenous knowledge integration - Local tradition consideration - Community values alignment
History	- History of free electricity access - Negative experiences from past failed projects - Resistance to changing traditional energy practices due to historical belief	- Community values/spirit - Past experience with energy solutions
Geographical	- Conflict/war zones - Disaster prone areas - Difficult terrain - Overly scattered settlements	N/A

Emerging patterns of identified barriers and enablers

A systematic review of 37 country case studies examined the landscape of off-grid community renewable energy initiatives across multiple dimensions (Table 5). The analysis revealed a significant focus on economic, technical, social, and political dimensions of these projects. Specifically, 100% of reviewed studies highlighted economic and technical barriers, with 96% identifying social barriers and 83% pointing to political challenges. In contrast, ecological (17%), cultural (26%), and historical (22%) dimensions received markedly less attention.

The review of enabling factors demonstrated a similar pattern. Economic and social enablers were present in 88% of case studies, followed closely by technical (85%) and political (85%) enablers. Notably, ecological (24%), cultural (27%), and historical (21%) enabling factors were less consistently documented across the reviewed literature.

Building upon these insights, a comprehensive cross-dimensional analysis revealed the complex interactions between barrier and enabler factors across multiple domains. Social-technical barriers emerged most prominently, appearing in 83% of cases and characterised by limited community engagement, skill shortages, and inadequate capacity building. These were closely followed by social-economic barriers (78%), such as manifesting through extreme poverty and low ability to pay. Economic-technical barriers appeared in 48% of cases, typically involving high upfront costs and maintenance challenges, while political-economic barriers were identified in 65% of cases, frequently linked to limited regulatory support and weak governance structures.

Correspondingly, the most effective enabler combinations underscored the critical importance of integrated approaches. Political-economic enablers in 76% of successful cases emphasised strong leadership, enabling regulatory environment, and long-term financing support. Social-technical enablers in 73% of cases focused on comprehensive community engagement and robust training programs, while socio-economic enablers in 61% of cases prioritised productive energy use and strategic tariff design.

A comprehensive cross-dimensional overview of community renewable energy projects revealed complex interactions between barrier and enabler factors across multiple domains. The most significant barrier combinations demonstrated intricate interconnections, with social-technical barriers emerging in 83% of cases—characterised by limited community engagement, poor design, skill shortages, and inadequate capacity building—followed closely by social-economic barriers (78%), which often manifested through extreme poverty and inconsistent income generation. Economic-technical barriers appeared in 48% of cases, typically involving high upfront costs and maintenance challenges, while political-economic barriers were identified in 65% of cases, frequently linked to limited regulatory support and weak governance structures. Correspondingly, the most effective enabler combinations highlighted the critical importance of integrated approaches: political-economic enablers in 76% of successful cases emphasised strong leadership and long-term financing support, social-technical enablers in 73% of cases focused on comprehensive community engagement and robust training programs, and socio-economic enablers in 61% of cases prioritised productive energy use and strategic tariff design. These findings underscore the necessity of holistic, multi-dimensional strategies that simultaneously address technical, social, economic, and political dimensions to successfully implement community renewable energy initiatives.

DISCUSSION

The review of post-implementation case studies provides valuable insights into effective strategies and challenges in implementing RES in off-grid communities. These case studies offer practical, context-specific guidance on translating theoretical, community-based approaches into actual RES practices.

Current established theories, frameworks, concepts, and guidelines on community energy and climate resilience have inherent limitations. Critiques highlight issues such as overreliance on local resources and potential disavowal of government in ABCD approach [110], inadequate cultural focus in SLA [111], and the problematic assumption of community homogeneity implied in CBA [41]. By combining key elements from practical and theoretical foundations, these limitations can be addressed.

The principles identified include: 1) people-centered approaches; 2) inclusive participatory processes; 3) locally and culturally appropriate solutions; 4) asset recognition and mobilisation; 5) mutual learning and transparent information sharing; 6) multi-stakeholder involvement; and 7) strong governance. These synthesised key principles are crucial for developing refined approaches that capture real-world RES implementation complexities. For instance, the application of *'place-based, locally and culturally appropriate, and community vulnerabilities reduction-focused solutions'*, is exhibited in a sustainable SHP operation in an indigenous community in Indonesia as indicated by Pratiwi & Juerges (2022) [104]. Similarly, Riley's (2021) success with Australia's Bushlight project in Kimberley through successful Aboriginal participation demonstrates the significance of *'inclusive, participatory processes'* [75].

Among the 37 country case studies examined, social aspects—while critical—are predominantly interpreted through economic and technical lenses (Table 5). The most significant barrier combinations highlight this limitation: social-technical barriers (83% of cases) and social-economic barriers (78% of cases). Similarly, the most effective enabler combinations reveal a narrow social perspective: social-technical enablers (73% of successful cases) and socio-economic enablers (61% of successful cases), as Figure 3 illustrates. A critical gap emerges in the understanding of socio-cultural interactions within off-grid community energy initiatives. The analysis revealed that socio-cultural dimensions were addressed in only 30% of case studies examining both barriers and enablers, representing a significant limitation in current research approaches. This underrepresentation suggests a profound scholarly oversight in comprehending the complex ways cultural contexts mediate community energy transitions.

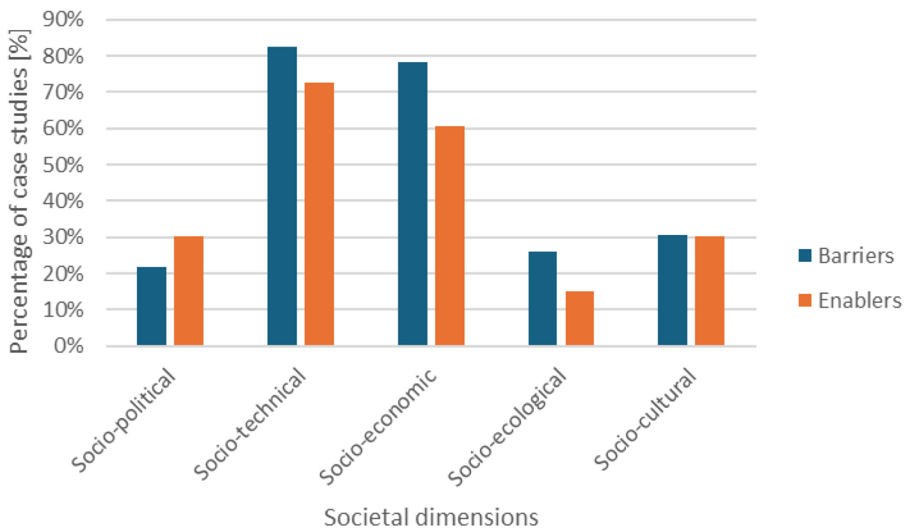

Figure 3 Interconnected social dimensions: Cross-sectoral analysis of barriers and enablers in 37 country case studies

Existing literature predominantly interprets social challenges through economic and technical lenses, neglecting crucial contextual elements, such as: indigenous knowledge systems, local value orientations, community-specific social dynamics, cultural narratives shaping energy perceptions. This reductive approach undermines a comprehensive understanding of how communities interpret technological innovations, engage with energy transition processes, construct meanings around environmental challenges, and develop adaptive strategies

This review highlights the urgent need for more sophisticated research frameworks that recognise culture as a fundamental, rather than peripheral, element of socio-technological transformations. Additional research gaps were observed in socio-political (22-30% coverage) and socio-ecological (15-26% coverage) interactions, further emphasising the need for more comprehensive, context-sensitive research designs. These findings align with Kumar's (2018) energy access research, highlighting the necessity for more studies on how local socio-cultural processes mediate development and energy project impacts [17], and Feron et al.'s (2016) further research suggestion, emphasising the critical need for more alternative approaches to energy solutions in remote communities that can accommodate diverse community needs [69].

Future strategies for RES implementation must prioritise ensuring cultural relevance, leveraging local knowledge, addressing social equity, preserving cultural identities, and facilitating effective communication and education. These approaches are essential for enabling community resilience and empowerment, moving beyond traditional techno-economic frameworks that often neglect contextual nuances.

Climate change impacts demonstrate significant variability across diverse communities, highlighting the critical role of socio-cultural context in identifying vulnerabilities and building adaptive capacity. By tailoring RES implementation to the specific needs and vulnerabilities of each community, researchers and practitioners can develop more responsive and sustainable energy solutions that enhance communities' ability to cope with and recover from climate-related challenges.

This perspective aligns with the study's earlier observations about the limited exploration of socio-cultural dimensions in existing research. It calls for a more holistic approach that:

- Recognises the unique cultural landscape of each community
- Develops context-specific energy solutions
- Prioritises community agency and cultural preservation
- Integrates local knowledge systems into technological interventions

CONCLUSIONS AND FUTURE DIRECTIONS IN FIELD

This systematic review reveals critical gaps in understanding off-grid community's RES implementation, highlighting the limitations of current theoretical frameworks and providing a roadmap for more comprehensive research approaches. The research exposes fundamental weaknesses in existing community energy and climate resilience theories, including overreliance on local resources, potential marginalisation of governmental roles, inadequate cultural focus, and problematic assumptions of community homogeneity.

The review synthesises seven key principles that can guide future research: people-centered approaches, inclusive participatory processes, locally and culturally appropriate solutions, asset recognition and mobilisation, mutual learning and transparent information sharing, multi-stakeholder involvement, and strong governance. These principles offer a critical framework for developing more nuanced approaches to RES implementation in off-grid communities.

The study's key contributions include exposing the narrow conceptualisation of social aspects in renewable energy research, highlighting the critical need for interdisciplinary research frameworks, demonstrating the importance of cultural contexts in technology adoption, and identifying significant research gaps in socio-cultural interactions. Better implementation of RES in the context of off-grid communities, as demonstrated by the review, requires a fundamental shift in approach. Researchers and practitioners must recognise local cultural knowledge, develop context-specific technological solutions, prioritise community agency, and integrate social-ecological perspectives. This approach demands capturing the intricate nuances of real-world situations that traditional techno-economic models often overlook.

Future research directions call for interdisciplinary methodological approaches, frameworks that centralise cultural contexts, research methodologies privileging local knowledge, region-specific studies, and exploration of nuanced socio-cultural interaction mechanisms. This review serves as a robust foundation for future comparative studies, exemplified by the forthcoming field exploration of RES in Australian and Indonesian off-grid communities, marking the next stage of this research to develop a best-practice framework, facilitating a more sustainable and impactful implementation of RES that is attuned to the unique needs and dynamics inherent in off-grid communities.

By transitioning to comprehensive, community-centered approaches, researchers and policymakers can develop more effective, sustainable, and culturally appropriate renewable energy solutions that genuinely address the complex needs of diverse communities. This approach represents a critical step towards understanding and implementing renewable energy systems that are not just technologically sound, but also socially and culturally meaningful.

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NOMENCLATURE

Abbreviations

ABCD	Asset Based Community Development
CBA	Community-based Adaptation

CCF	Community Capital Framework
CPR	Common Pool Resources
CRD	Climate Resilience Development
DFID	Department of International Development
FCR	Framework for Community Resilience
IIED	International Institute for Environment and Development
IPCC	The Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
LCOE	Levelised cost of energy
MW	Mega-Watt
O&M	Operation and maintenance
PUE	Productive Use of Energy
PV	Photovoltaic
RES	Renewable energy systems
SESF	Socio-Ecological System Framework
SHP	Small hydro power
SHS	Solar home systems
SLA	Sustainable Livelihood Approach

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APPENDIX

Practical case studies selected from a total of 37 countries reviewed.

No	Study and geographical region	Types of RE	Type of Project	References
1	Chile rural electrification program, Chile	Solar PV	Multiple projects	[69]
2	Esaghem Village, Cameroon	Solar PV	Single project	[16], [76]
3	Tanna Island, Vanatu	Solar PV	Multiple projects	[74]
4	Isle of Eigg, Scotland	Solar PV, wind, SHP and hybrid	Single project	[83], [96]
5	Australia Bushlight projects, Australia	Solar PV	Multiple projects	[75], [107]
6	Cobrador Island, Philippines	Solar PV-diesel	Single project	[89], [95]
7	Sengor, Bhutan	SHP	Single project	[90], [109]
8	Rural microgrids, Indonesia	Solar PV, SHP	Multiple projects	[54]
		SHP	Single project	[77], [85], [104]
9	El Alumbre, Campo Alegre, Alto Peru; Peru	Wind energy	Single project	[87]
10	Nepal's SHPs	SHP	Multiple projects	[91]
11	Bambadinca, Guinea Bissau	Solar PV	Single project	[86]
12	La Gran Sabana, Venezuela	SHP	Multiple projects	[81]
13	Gbamu Gbamu microgrid, Nigeria	Solar PV	Single project	[99]
	Nigeria microgrid program	Solar PV	Multiple projects	[71]
14	Western China electrification program	Solar PV, SHP, hybrid solar PV-wind	Multiple projects	[70]
15	Lucingweni, South Africa	Hybrid solar PV-wind	Single project	[73], [93]
16	Mombou, Douguia and Guelendeng; Chad	Solar PV	Multiple projects	[86]
17	Fort Chipewyan, Canada	Solar PV-diesel	Single-project	[82]

18	India solar mini-grids	Solar PV	Multiple projects	[78]
19	Alaska, United States	Wind-diesel	Multiple projects	[88]
20	Pediatorkope, Kudorkope and Atigagome; Ghana	Solar PV	Multiple projects	[102]
21	Malawi’s off-grid solar PV projects	Solar PV	Multiple projects	[72]
22	Dominican Republic’s micro hydro projects	SHP	Multiple projects	[97]
23	Nabouwalu – Vanua Levu, Fiji	Solar PV-wind-diesel	Single project	[92]
24	El Hierro, Spain	Hybrid wind-hydro	Single project	[103]
25	Monte Trigo, Cape Verde	Solar PV	Single project	[98], [105]
26	Pelelu Tepu, Suriname	Solar PV	Single project	[94]
27	Chipendeke, Zimbabwe	SHP	Single project	[106]
28	Soum Centers, Mongolia	Hybrid solar PV-wind	Multiple projects	[108]
29	Mpanta, Zambia	Solar PV	Single project	[79]
30	Agrienergie 5, La Reunion, French overseas territory	Solar PV (agriphotovoltaic)	Single project	[100], [101]
31	Kaur, Gambia	Solar PV	Single project	[86]
32	Steung Chrov, Cambodia	Solar PV	Single project	[84], [112]
33	Batzchocolá, Guatemala	SHP	Single project	[80]
34	El Espino, El Carmen and Itayovai, Bolivia	Solar PV	Single project	[80]
35	Powiakuru, Kangaruma and Shulinab, Guyana	Solar PV	Single project	[80]
36	Les Anglais, Haiti	Solar PV-diesel	Single project	[80]
37	La Guajira, Colombia	Hybrid solar PV-wind	Single project	[80]