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Research Insights and Knowledge Headways for Developing Remote, Off-Grid Microgrids in Developing Countries

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Abstract: Recent reports from international energy agencies indicate that more than a billion of the population in the world is deprived of basic electricity provisions, confined mainly to the remote communities of developing nations. Microgrids are promoted as a potential technology for electricity provisions to off-grid rural communities, but have failed to reach their value proposition in the context of rural electrification access. In view of the rampant rural electrification issues, the objective of this paper is to furnish an understanding of, and advance the knowledge into, methods to facilitate the design and development of microgrid systems for remote communities in developing countries. The methodology involves an integrative review process of an annotated bibliography to summarise past empirical or theoretical literature. As such, this research is based on evaluation attributes, and identifies the challenges and barriers for remote microgrids through an analysis of 19 case studies. The paper concludes by proposing key aspects that need to be considered for developing a framework to improve the sustainability of electricity provisions for off-grid rural communities in developing countries.

Keywords: rural microgrid; rural electrification; microgrid failures; multi-tier framework; remote electrification framework; sustainable energy

1. Introduction

Often described as the “Golden Thread”, sustainable energy access is a determinant factor for a country’s economic growth, human development index, and social equity [1]. These are the most crucial factors that determine a nation’s overall development and progress, particularly for communities and regions in developing countries, which have been identified as the energy deprived regions [2]. In 2016, the United Nations introduced sustainable energy goals (SDGs) with the 2030 Agenda [3]. This global action for local results, with an emphasis on rural regions, is based on the successful achievement of access to affordable and clean energy (SDG.7) [4].

The drive for universal access to electricity, especially, has resulted in technological advancements in the generation, transmission, and distribution of electricity. The endeavour for access to electricity has, however, been challenging in developing countries with a dominance of rural population [5]. The expansion of electricity has not been uniform, with the consequence of many rural communities having a lower social and economic status compared to urban areas. This demarcation between the urban and the rural scenarios is a major threat to the achievements of the United Nations Development Programme (UNDP) plan, which focuses on the strategic issues of poverty alleviation, democratic governance, climate change, and economic inequality [3,6]. The intention of a centralised electricity grid approach to bridge the gap between the rural and urban scenarios face hindrance due to various demographic, topographic, social, and economic factors [7–9]. However, with the perspective to bridge the gap of energy access in the rural and the urban scenarios, it gives rise to a major issue concerning the source of the energy access that is utilised. Over the years, initiatives have been undertaken by governments to extend the centralised grid, the electricity for which is generated primarily using conventional energy sources. The electricity approach for most of rural communities in developing countries has been egotistical with mere access to electricity rather than considering the sustainability of approaches towards achieving it. As such, a decentralised approach, in the form of a micro/mini-grid, has been recognised and put to use over decades, for a dual purpose. Firstly, it is an alternative for the centralised grid infrastructure to serve the purpose of end users of the rural communities. Secondly, it is estimated to save extensive capital investments for the maintenance of the ageing transmission and distribution (T&D) facilities for sparsely populated regions [10] in addition to environmental benefits [11]. In view of the advantages of a decentralised approach highlighted for electrifying a remote location, the following section of the article constitutes a literature review for remote microgrids in rural communities. The theoretical literature informs the research practices, and reviews the present state of art of research in the context of rural electrification in developing countries, further contributing to situate the objective of the research undertaken.

1.1. Literature Review of Remote Microgrids

Escalating research and innovation, as well as a competitive market in the renewable energy sector, have resulted in large cost reductions of the components associated with clean energy systems in relation to the traditional ways of electricity access [12]. The affordability of the renewable energy system components has directed varied research interest for decentralized off-grid systems, as is evident from the literature, which is broadly classified in terms of: review publications of off-grid systems in Table 1, research oriented towards micro-grid technology configurations and applications in Table 2, models and simulation methodologies for off-grid systems in Table 3, and case study analyses of different off-grid systems in various countries and locations in Table 4. Figure 1 illustrates the distribution of the research interests from a sample of 122 articles published in prominent journals.

Table 1. Review publications for off-grid systems.

S.no	Publication	Description
1	[13]	Review of an off-grid system based on the configuration, control strategy, techno-economic analysis, and social effect for a case study in India.
2	[14]	Review for a comparison of various standalone solar PV, grid-connected PV and HRES with a review on plug-in-electric vehicles (PEV) studied across the globe.
3	[15]	General framework to microgrid systems and an extensive analytical review of the literature for stand-alone and hybrid systems.
4	[16]	Review covering techno-economic feasibility studies and five methodological applications, namely the worksheet-based tools, optimization tools, multi-criteria decision-making (MCDM) tools, system-based participatory tools, and hybrid approaches.
5	[17]	Review and comparison of the stand-alone solar and hybrid solar systems based on case studies implemented for various locations throughout the world.
6	[18–20]	Overview of the status of clean development mechanism (CDM) portfolio for stakeholders' and assessment of potentiality of sustainable energy technologies for Thailand.
7	[21,22]	Simulation software tools reviewed for off-grid systems.

Table 2. Microgrid technology layout for off-grid systems (stand-alone and hybrid).

S.no	Publication	Description
1	[23–25]	PV based systems for irrigation and water pumping activities.
2	[26–30]	Technology for energy systems such as street lighting, solar charging stations, and solar charging.
3	[31]	Review of the various inverter topologies for PV systems in a grid-tied scenario.
4	[32]	Various configurations for charge controllers with importance on MPPT for PV based systems.
5	[33,34]	Typologies of nano-grids for DC systems with technologies of maximum power point tracking.
6	[13,35,36]	Technology layout for hybrid PV–wind energy system design for basic lighting and mobile phone charging provision purpose.
7	[37,38]	Solar smoother techniques for analysis of PV integrated systems and estimation of permissible PV penetration ratio.
8	[39]	Representation of the system model for rural electrification in Cameroon consisting of a hybrid wind–diesel battery technology.
9	[40,41]	Design and comparison of various hybrid configurations of energy systems consisting of PV–wind–diesel–battery systems.
10	[42–46]	Design and layout characteristics of hybrid systems for measuring fuel consumption and resultant energy productivity.

Table 3. Microgrid models and simulation methodologies (stand-alone and hybrid).

S.no	Publication	Description
1	[47]	A mathematical model for the performance estimation of wind-driven roto-dynamic pumps with a reasonable specific diameter for varying operating conditions for water pumping applications.
2	[48]	Simulation-based sizing curves developed for PV–battery and diesel–battery configurations.
3	[49]	Particle swarm optimization theory model for, aimed at management and provision of electricity and water to an isolated village in Nigeria
4	[50,51]	Incorporation of uncertainties in solar resource and component-based cost determination of energy systems.
5	[52–57]	Mathematical modelling and dispatch strategy analysis for energy systems with a case study analysis in Indian perspective.
6	[53,58–61]	Rural India perspective for energy management optimization model adhering to reliability and economic parameters.
7	[62]	Evolutionary based algorithm for dispatch strategies based on economic and environmental parameters.
8	[63]	Expanded transhipment model is proposed for modelling a hybrid power system with energy losses and for capacity estimation and storage requirement analysis.
9	[64]	Hybrid energy system designed with the incorporation of load shifting and energy storage techniques.
10	[65]	Probabilistic battery state model developed for evaluation of reliability analysis.

From the literature, it can be observed that most of the research focussed on individual technologies, or were site-specific, owing to off-grid systems having varied characteristic features with different value propositions for distinctive micro-grid segments. Figure 1 highlights a clear dominance of research on the techno-economic analysis (TEA) of off-grid systems based on case studies. However, the scientific literature suggests that much of the research has neglected considering a "unified electricity approach"(Step towards a reliable and feasible electricity provision for the various structural typologies and end use applications existing in the rural community, without targeting a specific end use application), due to a predominant approach towards a hierarchical preference for household electrification, compared to a holistic approach towards other structural typologies and aspects of rural community developmental needs.

Table 4. Microgrid techno-economic analysis (TEA) and case studies for off-grid systems (standalone and hybrid).

S.no	Publication	Description
1	[66–68]	Typology identification and corresponding renewable energy system identification technologies in the African context.
2	[69–76]	Standalone microgrid systems with single source systems globally used for various applications ranging from street lighting, household electrification, school electrification, and community electrification in developing countries.
3	[15,77–85]	Various decentralized hybrid energy systems with a techno-economic analysis for the provision of electricity to the developing countries with energy scarcity, developed countries for energy management and load sharing purposes.
4	[86–95]	Substantial information regarding the off-grid scenarios considering a Nigerian perspective and can be used as the background study for the present research. However, the system comprises of a single source which is supposed to face intermittency in power generation. This corresponds to the fact that the solar energy output can be highly fluctuating with effects of cloud passing, shading, soiling, and derating factors of PV.
5	[5,96–121]	Techno-economic analysis of various decentralized energy systems, considering the importance of electricity access to the energy dearth communities and islands has been discussed in Asian perspective. An emphasis has been given to electricity provision for houses. The energy access to the developing countries has been the focus with varied case studies for system sizes ranging from 0.2–100 kW.

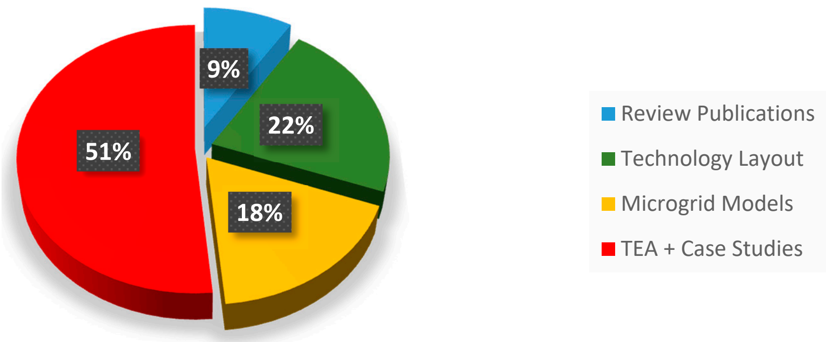

Figure 1. Distribution of microgrid research from a sample of 122 research articles.

Nevertheless, the literature still lacks a detailed standard framework that can be considered for the cross-sectional evaluation of the long-term sustainability of off-grid, remote electrification systems. To decimate the techno-economic challenges of rural electrification systems, an understanding of both successes and the barriers towards sustainable, rural, off-grid systems is required. This may result in achieving widespread scaling of the deployment of rural micro-grids and provide better insights into the factors influencing the hindrance towards the SDGs.

1.2. Objective and Approach of the Paper

In view of the shortcomings identified in the previous section, the objective of the paper is to provide insights to advance the knowledge into methods to facilitate the design and development of remote microgrid systems for remote communities in developing countries. To this end, the paper evaluates the functional state of off-grid renewable energy systems in the context of rural electricity access in developing countries. The paper is aligned in accordance with the objectives outlined by the IEEE Working Group on Sustainable Energy Systems for Developing Communities (SESDC) [122]. Figure 2 shows the research approach and the scheme of the paper. The Technology and Policy Assessment (TPA) approach, developed by the UK Energy Research Centre to inform decision making processes, was adopted and informed an annotated literature review for gathering information, determining the dimensions of the study, and establishing the development of evaluation criteria based on identified attributes that can potentially impact the proper functionality of remote off-grid microgrid systems. The attributes were considered as parameters to assess 19 rural microgrid cases in the Asian and African context, owing to the detailed experiences reported in the literature based on interviews and surveys. The knowledge headways were then formulated, based on lessons learned from the shortcomings highlighted in the evaluated cases.

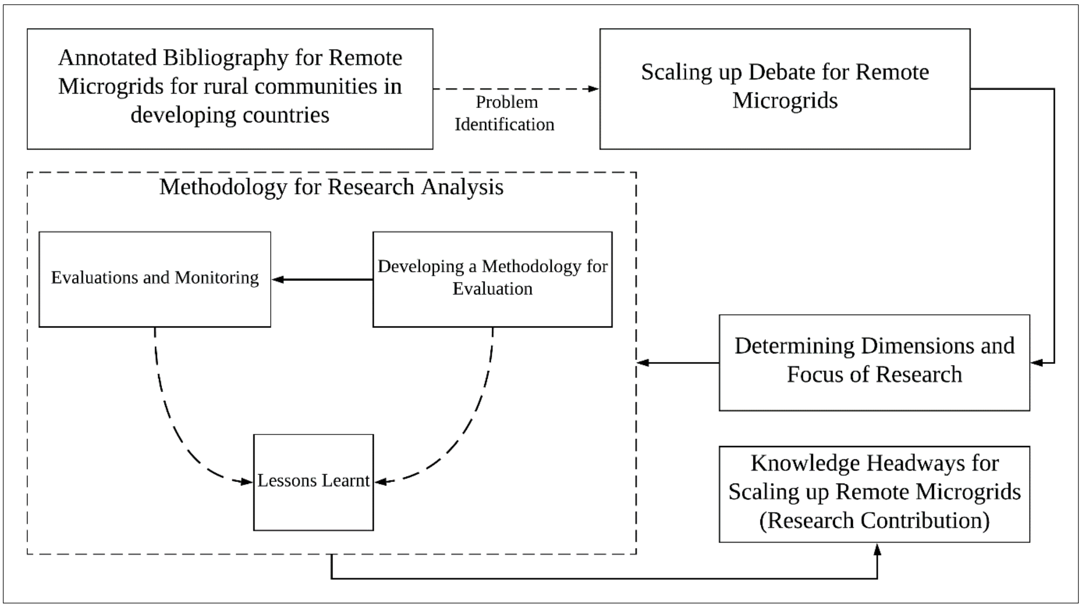

Figure 2. Scheme and the objective of the paper.

2. Evaluation of Micro-Grids in Rural Communities

As stated in the previous section, the methodology is based on the evaluation of case studies of rural microgrids. However, it is necessary to define the evaluation criteria or factors to successfully assess the functionality and sustainability of a microgrid system in the context of developmental activities. To this end, the study adopted a "complex nesting of studies within frames of reference that themselves resulted from still other lines of studies" [123], to establish attributes that suit an evaluation of the current operational status of microgrids. Several case studies, of micro-grids for rural communities in developing countries, available in the scientific literature, were used as a basis to define the principles for the evaluation.

The attributes used for the evaluation comprise of: Capacity, Availability, Affordability, Reliability, Legality and Sustainability (CAARLS). The attributes of capacity, availability, affordability, and reliability have been derived from the multitier-framework (MTF), identified by the Energy Sector Management Assistance Program (ESAMP) [124] as the criteria for microgrid evaluations, which are specifically technology neutral ("Technology neutrality means that the same regulatory principles should apply regardless of the technology used. Regulations should not be drafted in technological silos") [125] and accounts for both the on- and off-grid energy systems in the rural and urban context [126]. These attributes evaluate the energy access (electricity, cooking, and heating) for household, productive and community usage as a holistic approach, and not electricity access in specific.

Also, the MTF evaluates energy access by classifying the energy systems based on Tier levels ranging from Tier 1 to Tier 5, which, we argue, are not adequate, because: (1) The tier levels are not confined to any rural context in particular; and (2) the energy (and electricity) usage pattern and demand in a rural scenario differs to an urban scenario, confining to a lower load factor and uncertain day-to-day random variability. These limitations of using MTF for evaluating rural electricity provisions is highlighted in [126]. MTF is a holistic approach for evaluating energy access and not electricity access in particular, and does not consider the real objective of remote electrification, which is the provision of basic electrical needs that can overcome the social barriers existing in the villages, due to a lack of electricity access. These factors highlight a need for a change in paradigm approach to assess electricity systems for a rural context, which are demographic oriented. As such, confining tiers based on the usage of electrical appliances, for the rural and urban scenarios as a holistic approach, lacks a feature-by-feature comparison. Moreover, the primary objective for scaling up or introducing remote microgrid for a rural community lies in the provision of "basic electricity access by identifying necessary electrical appliances" aimed for overall social well-being.

As such, in addition to the technical and economic attributes emphasised in the MTF, the social factors are deemed to be equally crucial in rural energy projects. The energy system challenges generally indicate a lack of understanding of the dynamic interaction of the energy system with the wider community, and a misalignment with societal development objectives. There is a distinct difference between energy provision that improves living conditions, such as lighting, and energy provision that enables productive activities and social well-being. Only with the latter will economic and social transformation occur, which, in turn, entail different behaviours and energy consumption patterns for an improved remote electrification scenario.

Thus, microgrids must cater to the community's needs which can be electrified, and that evolve over time. This requires a change in paradigm with respect to microgrid utilisation, evaluation, and application, and is the domain of resilience assessment, which should form part of the energy systems' design process. To overcome the inadequacy of the MTF to be directly used for rural microgrid evaluations, to consider the social and developmental aspects, and to practice future research efforts for remote microgrids, the study used two additional attributes, termed as 'legality' and 'sustainability', as an essential feature for evaluating the remote microgrids. The attribute 'legality' refers to challenges arising due to a lack in proper regulatory enforcements for rural electricity infrastructures and projects. The attribute 'sustainability', refers to an energy approach involving only renewable energy sources for electricity generation, in remote locations of the developing nations. In other words, microgrid systems that do not require the purchasing of fuels.

The attributes are then described as follows with the means to assess each:

- Capacity: The demand-supply matching of the electrical energy is by far an important factor in the process of designing a power system [127]. The capacity attribute of a micro-grid for a rural community is a multi-criterion factor, which requires an understanding of the complex nature of the techno-socio-economic system. The MTF evaluates the capacity attributes using two scales. The first scale is an indicator for meeting the peak-power and daily energy needs of the consumers. The second scale comprises the electrification services required that can be incorporated for the consumers, where the choice for the type of appliances plays a crucial role. The first scale corresponds to the technical viability of rural electrification systems, whereas the second scale indicates the social viability and standard of the rural community.
- However, a steady increase, in both the scales, can lead to divergent consequences, and thus can have an impact on the overall rural community electrification development process. An increase in the second scale is a developmental process towards a higher social standard and lifestyle of the rural community, whereas a hike in the first scale can lead to a system failure with an unplanned annual growth rate of electricity access. Also, the attribute for capacity plays a role in determining the scope of capacity extensions during, or at the end of, the project lifetime of an energy system, with additional indications for an improvement in services for a certain energy system project at a pilot stage. The capacity attribute can thus be accessed by answering the following questions:

  - (CQ1) To what extent did the project engage an active community participation in the load estimation and futuristic load growth mapping techniques?
  - (CQ2) Are the energy efficient practices incorporated into the system design and operational stages?

- Availability: This attribute focuses on the availability of power supply for end use applications. The two indicators that govern the evaluation criterion are the day-hours supply of energy access (electricity), and the electricity supply hours in the evening. This attribute can determine the status of the microgrid project designed or implemented for useful applications and determine the scope for project improvisations. In most of the rural communities, electricity access is prioritised in the daytime for agricultural chores and varied cottage industries, with evening access to electricity to the households and communities being avoided. The evening supply of electricity is important to evaluate, as it has the potential to improve the social life of the dwellers. For example, by providing electricity to students, thereby extending their hours of study and also for community development and leisure time activities. Although the MTF scales the availability of evening hours of electricity access to a minimum of four hours per day, the questions that need to be assessed involve the energy suppliers and the end users:

  - (AvQ1) At the supplier end, what is the energy utilisation factor of the system?
  - (AvQ2) To what tier level does the availability conform to, considering the end user satisfaction towards energy access?

- Affordability: This evaluation criterion is based on the economic aspects of the micro-grid, generally considered the "willingness to pay" from a consumer perspective [128]. However, the meaning of term is often misinterpreted, being used to discuss the affordability of the system from a developers' perspective to compensate for the operational and replacement costs that are incurred during the overall lifetime of the project. At the consumer end, the "willingness to pay" is an indicator concerning the annual income of the respondent and is a reflection towards the socio-economic aspect of the consumers involved in the community project. Also, the attribute affordability at developers' end, can be extended to understand the nature of the project in adapting itself to project expansions at the end of the project lifetime of a micro-grid supposedly to be around 25 years and also the flexibility in terms of cost incurred during the operational stage of the project for component replacement purposes thereby, reflecting on the foundation of the techno-economic aspect of the micro-grid project. The attribute can be accessed by answering the following two questions at the pre- and post-project assessment stages:

  - (AfQ1) At the pre-project stage, is the income level of the energy despondent capable to pay for the cost of energy?
  - (AfQ2) At the post-project stage, are the revenues earned, during the operational stage and at the end of the project lifetime, enough for the replacement cost of the system components?

- Reliability: This attribute is aligned with the previous factor of availability. However, the distinctive feature of reliability indicates the frequency of interruptions and the time elapses for the system to regain the original state of generating electricity, thereby indicating a system's autonomy. As such, the reliability attribute can be considered 'the resilient nature of the microgrid', indicating the maximum hours for which the generation of power can be disrupted. The power interruptions in a renewable energy system may arise due to technical failures or malfunctioning of the power system components, or of interruptions due to natural phenomena, such as days of less sunshine, excessive winds, or natural disasters such as earthquakes and floods. Therefore, the microgrids are to be assessed by answering the following questions:

  - (RQ1) Are there alternative approaches for energy access, to meet the community needs, in events of power generation interruptions?

  - (RQ2) What is the annual percentage of hours of power interruptions for the micro-grid?

- Legality: This evaluation attribute in the context of developing countries corresponds to the barriers to the micro-grid projects, such as incompetent policies for rural electrification, lack of legal documents for revenue shares, lack of legal procedures for property transfers for the project, and the lack of conformity of the projects to technical standards. The following questions may be asked:
  - (LQ1) Is the ownership structure and institutional support of the micro-grid system clearly defined?
  - (LQ2) Are supporting policy guidelines available, efficient for the deployment and successful functionality of the micro-grid project?

- Sustainability: Another important aspect that needs attention for the evaluation of the rural micro-grids is the attribute of sustainability of the project. The MTF does not consider this evaluation criterion. However, the evaluation criterion of sustainability is deemed crucial for achieving SDG.7, where green energy access of electricity can lead to accomplishing a holistic approach towards the SDGs. The attribute 'sustainability' is thus confined to assess the utilisation of renewable energy sources only for electricity generation. The evaluation aspect can be utilised to access the sustainability of the project at the design stage of the project with life cycle assessments, further during the operational stage of the project, and also at the end of the project lifetime by defining a proper disposal procedure of the system components. The two questions are subsequently the following:
  - (SQ1) Is the micro-grid system based on a 100% supply of electricity from renewable resources?
  - (SQ2) Are the environmental implications over the life cycle of the project comprehensively considered?

3. Research Analysis Based on CAARLS Attributes

As stated in [129], "data on reasons for microgrid failure and success simply do not exist in the appropriate depth and detail for a large number of cases, so at the very least, our report begins a process of providing an in-depth analysis on a few cases". The literature on rural electrification and microgrids contain sufficient generalised advice on best practices and user-centric approaches. However, it lacks in particulars in terms of the approach of the project developers of promoting remote electrification for geographic constraint locations. Also, the literature lacks enumerating particulars on success-failure details of specific community energy systems with a diversity of stakeholders, including a wide variety of ownership models, developer objectives, community participation, energy source-generation technologies, and the practitioners' perspectives.

Considering the challenge of selecting case studies with missing data, as stated in [130], a report, published by the United Nations Foundations [131], was consulted, which details case studies of microgrids for developing countries, based on the layers of complexity approach, rather than focusing on the controlled variable approach. The case studies detailed in the report are based on personal interviews and surveys, and was found appropriate for the study, considering a blend of the techno-socio-economic and cultural circumstances details, important for analyzing microgrid challenges based on the evaluation attributes. As such, instead of capturing a wide breadth of microgrid services and technology practices around the globe, the study focused on the depth of electricity challenges prevailing in the world's most energy-scarce communities. The remaining case studies selected for the analysis of the research, were identified using the 'advanced search' option available in Google Scholar, thereby searching articles with the 'exact phrase' option as "techno-economic analysis of microgrids in sub-Saharan African countries" and also, by using keywords ("remote microgrids"; "rural electrification projects") in the option 'find articles with all of the words'. Consecutively, a similar approach was performed for other countries in the Indian subcontinent. The focus for selecting the case study to specific regions was subjected to the sample countries that will form the foundation to detailed case studies, with similar if not exact demographics and electricity issues for rural communities. Moreover, this research adheres to the objectives and the tasks outlined by the IEEE Working Group on Sustainable Energy Systems for Developing Communities (IEEE SESDC) [132] with a focus to raise awareness about challenges to provide universal access to electricity related issues in developing communities around the globe. The cases that have been considered for the research constitute a mix of theoretical and implemented microgrid projects.

Table 5 summarises the 19 case studies and the corresponding levels of compliance to the attributes of the CAARLS framework. The contrast of the colours determines the level of the barriers affecting the microgrids. The levels have been categorised into high barrier level in red, low barrier level in blue, low success level in green, and yellow for cases where enough information was not available.

From a capacity perspective, it was found that a microgrid may satisfy the basic design model to supply electricity for 4–6 h during the daytime, but fails to cater for the needs in the evening hours, which the associate community may require. A potential reason underlying the failure for a system to deliver evening hours of electricity was due to the designing of microgrids constituting renewable energy based systems with no battery banks. The feature of the microgrid providing electricity only during the daytime indicates an inadequacy in the pre-assessment stages of the microgrid design in terms of community participation.

On assessing the microgrid functionality based on the capacity attribute questions, few implemented microgrids met the average annual energy growth, due to the changes in the energy behavioural pattern of the users, resulting in their discontinuation before their scheduled lifetime. These factors also indicate a lack in the pre-assessment planning stage to adequately consider any vital changes/variations that affect the system operational cost and functionality over the lifetime due to, for example, changes in the fuel cost or degradation of the components.

Also, the assessment revealed microgrids comprised only of a standalone energy source system with no provisions for an alternate energy source or a battery storage system. This often restricts the electricity supply to a limited number of hours, thereby reflecting a low tier-level of electricity access (availability attribute) which affects the 'willingness to pay' factor among the village dwellers. A lower customer satisfaction level for electricity availability leads to payment disputes, resulting in poor revenue collection for the energy supplier. A lower cost recovery from the microgrid projects compels the nodal agencies to limit their services for maintenance and replacements of faulty components. Also, for one case study, the microgrid project provided electricity to the dwellers at a cost higher than the average annual income of the villagers. Thus, an issue of affordability plays an important role in determining the promotion and operation of the microgrids in remote locations. Although the factor of affordability mostly applies to the implemented systems, the theoretical systems in the scientific literature fail to convey the behavioral aspect of the users in the community towards the affordability aspects for the microgrid systems.

Table 5. Compliance level and attribute scorecard for the remote microgrid case studies based on CAARLS attributes.

Project Type	Project Cases and Location *	Project Status **	CAARLS Attributes					
			Capacity	Availability	Affordability	Reliability	Legality	Sustainability
Implemented Project Case Studies	CREDA, India [131]	PF	X	X	X	X	X	✓
	OREDA, India [131]	PF	X	X	X	X	X	✓
	WBREDA, Sagar Island, India [131]	NF	X	X	✓	✓	X	✓
	Desi Power, India [131]	F	X	X	✓	X	X	✓
	Mera Gao Power, India [131]	F	X	X	✓	X	X	✓
	Husk Power System, India [131]	F	X	X	X	✓	X	✓
	UREDA, India [131]	PF	X	✓	✓	✓	✓	✓
	Gram Oorja, India [131]	PF	X	✓	✓	X	✓	✓
	Green Empowerment/Tonibung/Pacos (GE/T/P), Malaysia [131]	PF	✓	X	X	X	X	X
	Electricity of Haiti (EDH), Haiti [131]	NF	✓	✓	X	✓	✓	X
	South Africa, [133]		X	X	X	X	X	X
Literature Based Case Studies	Nigeria [89]	NI	X	X	NA	X	X	X
	Pakistan [134]	NI	NA	X	NA	X	X	X
	Bangladesh [135]	NI	X	X	NA	X	X	X
	Bangladesh [136]	NI	X	X	NA	X	X	X
	Bangladesh [137]	NI	X	X	NA	X	X	X
	Kenya [138]	NI	X	X	NA	X	X	X
	Nigeria [139]	NI	X	X	NA	X	X	X

■: High Barrier Level; ■: Low Barrier Level; ■: Low Success Level; ■: Not Applicable; * CREDA—Chhattisgarh Renewable Energy Development Authority; OREDA—Orissa Renewable Energy Development Authority; WBREDA—West Bengal Renewable Energy Development Authority; UREDA—Uttarakhand Renewable Energy Development Authority; ** F—Implemented and functional; PF—Implemented and partially functional; NF—Implemented and non-functional; NI—Not implemented; NA—Information not available. * CREDA—Chhattisgarh Renewable Energy Development Authority; OREDA—Orissa Renewable Energy Development Authority; WBREDA—West Bengal Renewable Energy Development Authority; UREDA—Uttarakhand Renewable Energy Development Authority; ** F—Implemented and functional; PF—Implemented and partially functional; NF—Implemented and non-functional; NI—Not implemented; NA—Information not available.

From a reliability perspective, substantial information on the system design component failures, adversities and solutions to deal with them can be found in the literature, as indicated in a seminal research [140], however, in considering the remote off-grid scenarios, the majority of the implemented microgrids were found in a partial functional state, while some microgrid systems stalled after a few years of operation. This is likely because the degradation factors of the components were not factored well during the design stage, resulting in an inadequate response to timely system replacement and capacity extensions of the system. Amidst other technical failures, constant electricity tapping, and electricity thefts lead to overloading the systems, resulting in long hours of load shedding and poor power quality factors in the remote locations. Also, an inefficient energy utilisation of some of the systems, in addition to an inadequate management of the electricity supply at the user end, often lead to system disruptions and prolonged system failures. A few cases indicated disruptions in electricity supply over month periods due to natural and climatic catastrophes, and the challenge for the systems to gain full operational status, thereby highlighting a major lack in system resiliency approaches by the design engineers.

The assessment of the legal attributes highlighted ample unanswered questions of regulatory procedures that need strategic solutions. The contrasting issues of project and land ownerships, equity shares, and the energy supplier–customer relationships, indicated a major shortfall in the implemented microgrid projects. The security of the energy projects at stake, from theft and vandalism, was also found to be an obstacle towards the proper functionality of the energy projects. Research [141] detailing the various aspects of impact of theft and vandalism affecting the remote off-grid microgrid projects, and a report [142] informing a critical issue of copper metal wire thefts and thefts/damage to photovoltaic panels, highlight the security issues aligned with microgrid projects.

The attribute for sustainability had some mixed results, where many of the implemented cases used only a solar PV as their energy resource, and few cases completely relied on diesel generators. The theoretical cases available in the academic literature, indicate design parameters for the system diverging from using 100% renewable energy resources to serve the peak load demands. The cases also demonstrated a lack of introducing more efficient energy usage patterns among the communities.

The evaluation also highlighted the dynamic interaction between attributes. Figure 3 provides an example of the dynamicity of the 'legality' attribute, where important issues—such as "willingness to use and pay for energy services", "understanding and acceptance for fiscal revenue structures", and "community-centric energy satisfaction conformity"—often get overlooked by techno-economic evaluations, thereby failing to implement sustainable solutions.

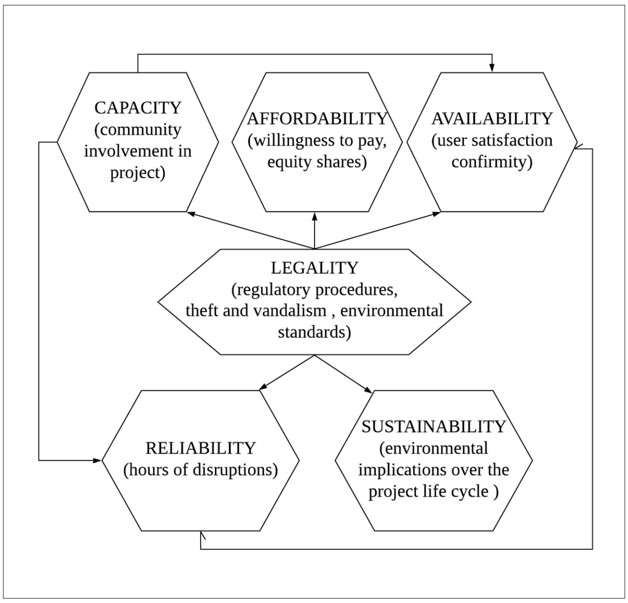

Figure 3. Attribute relationship diagram of the CAARLS attributes.

4. Conclusions and Further Research Considerations

The paper identifies the challenges that lead to inadequate remote microgrid systems, with the consequence of underestimating the value proposition of microgrids. However, the shortcomings in current practices and research efforts can be addressed for scaling up remote off-grid electrification, through three categories of interventions.

1. Definition of 'microgrid': There is a need to redefine the paradigm of a microgrid, with respect to the long existing definition proposed by US DOE (A microgrid is a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island-mode.) [143], to be more inclusive of the societal needs that dynamically change over time, thereby ensuring the resilience and sustainability of the overall system.
2. Framework for a system analysis approach: A framework is required for a system analysis approach that addresses the shortfalls of current techno-economic analyses approaches. Such a framework needs to address the following:

    - Typology identification: A classification of the village characteristics, the purchasing power parity of the villagers, the purpose of the electrification requirement, and the existing structural archetype of the village should be established. A proper system typology would assist in avoiding discrepancies in the identification of appropriate system parameters and sizing.
    - Revising the IEC/TS 62257-2 standard: A revision is seen as a necessary step in the classification of the energy sources for rural electrification mentioned in the IEC/TS 62257-2 Section 5.7 Table 4 "Typology of decentralised electrification systems" and Figure 2 "Systems Architecture and dispatchable energy", owing to an effective usage of the renewable energy sources for an off-grid system as part of the objectives of SDG.7 and a the inclusion of a battery storage unit as a mandatory step for designing a 100% renewable energy system.
    - Pathway for electrification planning techniques: An effective pathway towards examining each individual electrification system or load estimation, instead of a total average load estimation, as part of a collective electrification system for the entire village, could be a way forward towards a 'unified electricity approach' in the remote communities. This then depends on the services required, rather than considering an inventory average distribution of electrification for the entire village.
    - Energy utilisation and management techniques: The various cases report that failures occur due to inadequate power generation in a hybrid resource-based system. This leads to a technically unstable and economically unfeasible electricity solution over the project lifetime. A proper energy mix for the resources, involved in the process of power generation for the system, will yield to better management of resources. Also, proper resource management would augment the service life and performance of the system parameters. Furthermore, an active effort in proper energy utilisation and management technique would ensure an overall reduction in replacement time of the storage units and an effective cash flow assessment, resulting in an escalation of the salvage value of the system parameters at the end of the project lifetime.
    - A resilient approach for microgrid systems: The autonomy of the system, which has been neglected in the literature, is suggested to have a substantial impact on the overall reliability aspect of the microgrid system. A microgrid without a system autonomy technique would still be able to balance the load requirement for standard operating conditions, but inadequacies arise in events of power outage due to a fault in the power system components or in events of natural catastrophes. A resilient approach towards microgrid design, accounting for

irregularities, can be seen as a fundamental task for an uninterrupted power generation to the end use application. As such, an effort to redefine the existing definition of a microgrid, with an emphasis on a resilient approach, is an important step towards revising the value proposition of microgrid.

- System dynamics approach: The generation of power, with the use of renewable energy for the electrification, can vary due to the intermittency and variation in the sources. Also, the effect of changes in the energy ladder plays a vital role in the overall system performance over the project lifetime. In order to prevent jeopardising the system lifetime, a sensitivity analysis of the microgrid system should be performed to analyse the impact of the variations arising in the system. The variations can be in the form of cost inflation, load growth, system degradation, and energy resource fluctuations. The sensitivity analysis would, therefore, ensure an uninterrupted functionality of the microgrid system even in the worst-case scenarios thereby improving the overall system redundancy.
- Pathway for technology adoption: In order to prevent microgrid failures and enhance the acceptance of the system, technology adoption plays a vital role. These technologies would be directed towards ensuring the engagement and participation of the end users in the pre-post project phase. The involvement of the end users, project developers, project consultants, and implementers prior to the system implementation would likely establish the liabilities during the system sizing process. Also, post-implementation, the duties and the responsibilities of the participants can be established for the successful operation, maintenance, and replacement of the system over the project lifetime. The technology adoption process in addition to technical aspects should ensure the awareness regarding the projects on grounds of social, environmental impacts, infrastructure security, and critical issues of power theft.

3. Policy recommendations: A policy framework is required for the construction, transfer of ownership, and operation of distributed generation systems.

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