A Conceptual Framework to improve the design of sustainable off-grid microgrid systems for remote communities in developing countries

By:

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This thesis is dedicated to "Maa – Baba."

&

"Our planet Earth" for a Sustainable Future

Abstract

From job creation to economic development, from security concerns to the full empowerment of women, energy lies at the heart of the Sustainable Development Goals (SDGs) - agreed to by the world's leaders in September 2015 as part of the 2030 Agenda. In the words of former UN Secretary-General Ban Ki-moon, "Energy is the golden thread that connects economic growth, increased social equity, and an environment that allows the world to thrive." Approximately 1 billion people in the world today have no access to electricity, and the issues are dominating in the remote communities of the developing countries.

Decentralized systems have existed over a couple of decades to provide electricity provisions in the off-grid communities devoid of the necessary energy services. The literature, however, suggests that off-grid systems have failed in delivering the tasks set forth to curb the electricity crisis. The crisis has resulted in communities primarily residing in the remote/islanded areas having lower social and economic status compared to the urban areas with centralized grid connectivity. A further review of the literature points to a lack of a detailed standard framework for cross-sectional evaluation of sustainability and reliability of the off-grid systems, which results in non-uniformity of the universal electricity access.

Given this, the main objective of the thesis is to establish a conceptual framework to improve the design of remote off-grid microgrid systems through a Techno-Economic Assessment (TEA) approach, by implementing a mixed-research approach. The research

strategy adopted to advance knowledge and for achieving the objective of the research follows the Technology and Policy Assessment (TPA) approach, developed by the UK Energy Research Centre (UKREC). The research evaluation design involves formative evaluations where questionnaires designed for investigating failure cases of remote microgrids are introduced, and a conceptual framework is developed, based on the lessons learned.

The conceptual framework comprising of modules incorporates essential features of improving the TEA of the remote microgrids and emphasizes on features like stakeholder assessments, sustainability aspects, energy management, and improving energy efficiency as well as overall system autonomy of the rural off-grid systems. Furthermore, following the TPA approach, the conceptual framework has been verified by involving a focus group. IEEE-Sustainable Energy Systems for Developing Communities (SESDC) was involved in the research verification process. The proposed conceptual framework was validated by incorporating a quantitative analysis to situate the research findings.

The research findings in the thesis contribute extensively to the body of knowledge by establishing a standard framework indicating the importance of energy-efficient approaches towards scaling up sustainable remote microgrids for solving energy crisis issues. As it were, the practical contribution of the thesis is critical in identifying and characterizing the dimensions of the Sustainable Developing Goal 7 for “affordable, reliable, sustainable and modern energy for all” and its impact on the other SDGs, thereby enabling progress towards the target 2030 of the United Nations.

List of Publications

1. **Chatterjee**, D. Burmester, A. Brent, and R. Rayudu, "Research Insights and Knowledge Headways for Developing Remote, Off-Grid Microgrids in Developing Countries," *Energies*, vol. 12, no. 10, p. 2008, May 2019.

2. **A. Chatterjee,** A. Brent, R. Rayudu, and P. Verma, "Microgrids for rural schools: An energy-education accord to curb societal challenges for sustainable rural developments," Int. J. Renew. Energy Dev., vol. 8, no. 3, p. 231, Oct. 2019.

3. **A. Chatterjee** and R. Rayudu, "Techno-economic analysis of hybrid renewable energy system for rural electrification in India," in 2017 IEEE Innovative Smart Grid Technologies - Asia: Smart Grid for Smart Community, ISGT-Asia 2017, 2018.

4. **A. Chatterjee**, A. Brent, and R. Rayudu, "Distributed Generation for Electrification of Rural Primary School and Health Centre: An Indian Perspective," in International Conference on Innovative Smart Grid Technologies, ISGT Asia 2018, 2018.

5. **A. Chatterjee**, D. Burmester, A. Brent, and R. Rayudu, "Defining a remote village typology to improve the technical standard for off-grid electrification system design," in 2018 Australasian Universities Power Engineering Conference (AUPEC), 2018, pp. 1–5.

Acknowledgement

"Arise, awake, and stop not till the goal is reached"- Swami Vivekananda

A statement that always encouraged me to desire for the best and to be hopeful when in doubts, during "my journey of Ph.D."

For the journey of my Ph.D., special gratitude goes out to my Ph.D. supervisors (Prof Alan Brent, Associate Prof Ramesh Rayudu and Dr. Daniel Burmester) "*who kept a sense of humour when I had lost mine*," and for their selfless time and care that kept me going. I thank colleagues from my research group (SPRES and Sustainable Energy Systems), officemates of AM 409, the wider ECS community at VUW, and the Victoria Doctoral Scholarship for their support that enabled me to pursue my research and complete this thesis. I am grateful to all my teachers for being an essential part of my entire academic journey. I specially mention the IEEE Working Group on Sustainable Energy Systems for Developing Community (WGSESDC) for all the insightful discussions during my research.

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Glossary of Terms

Attributes: Key elements or features (capacity, reliability, availability, affordability, legality and sustainability) regarded as a characteristic of microgrid assessments.

Autonomy: Autonomy is the number of days that the battery bank can supply the average load in cases of faults arising in system before being depleted, assuming it is not recharged during this period.

Framework: a basic structure underlying a visual representation of a system, concept, or text. It incorporates the fundamental problem, stressors, and stressor regimes to render a holistic understanding of the problem and its components for a pragmatic system solution.

Knowledge Headways: Advancing knowledge based on the evaluating research literature and studies.

Toolkit: Annotated set of downloadable information in form of documents or software tools describing the application of renewable energy technologies and project developments

Abbreviations

AOMR: Acceptance, Operation, Maintenance, and Replacements

CAARLS: Capacity, Availability, Affordability, Reliability, Legality, and Sustainability

ESAMP: Energy Sector Management Assistance Program

IEC: International Electrotechnical Commission

IEEE: Institute of Electrical and Electronics Engineers

LEDS: Low Emission Development Strategies

MDG: Millennium Development Goals

MTF: Multitier-Framework

NREL: National Renewable Energy Laboratory

SDG: Sustainable Development Goals

TEA: Techno-Economic Analysis

TPA: Technology and Policy Assessment

UKREC: United Kingdom Energy Research Centre

UNDP: United Nations Development Programme

WGSESDC: Working Group on Sustainable Energy Systems for Developing Communities

Chapter 1

Introduction

In the words of former UN Secretary-General Ban Ki-moon, "Energy is the golden thread," and 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, identified as the energy-deprived regions [2]. To aid this progress, in 2016, the United Nations introduced the Sustainable Development Goals (SDGs) with the 2030 Agenda [3]. This global action for local results, with an emphasis on rural regions, is based on the achievement of access to affordable and clean energy (SDG.7) [4].

The drive for universal access to electricity has, primarily, resulted in technological advancements in the generation, transattrmission, and distribution of electricity. The endeavour for access to electricity has, however, been challenging in developing countries with a dominance of the 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 significant 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 [6], [7]. It is, indeed, the case that the intention of a centralized electricity grid approach to bridge the gap between the rural and urban scenarios faces challenges owing to various demographic, topographic, social, and economic factors [8]–[10].

Over the years, initiatives have been undertaken by governments to extend the centralized grid, where electricity is generated primarily using conventional energy sources. The electricity approach for most of the rural communities in developing countries has been egotistical with mere access to electricity, rather than considering the sustainability approaches towards achieving it. As such, a decentralized approach, in the form of a micro/mini-grid, has been recognized and used over decades, for various purposes. This decentralized approach is an alternative for the centralized grid infrastructure to serve the purpose of end-users of the rural communities. The micro/mini-grid is also estimated to save extensive capital investments for the maintenance of the ageing Transmission and Distribution (T&D) facilities for sparsely populated regions [11], in addition to environmental benefits [12].

1.1 Research Rationale[1]

The escalating research and innovation, as well as a competitive market in the renewable energy sector, have resulted in substantial cost reductions of the components associated with renewable energy systems compared to the conventional ways of electricity access [13]. The affordability of the renewable energy system components has directed varied research interests for decentralized off-grid systems. The growing interest is evident from the literature, which is broadly classified as review publications of off-grid systems in Table 1.1 research-oriented towards microgrid technology configurations and applications in Table 1.2, models and simulation methodologies for off-grid systems in Table 1.3, and case study analyses of different off-grid systems in various countries and locations in Table 1.4. Also, Fig 1.1 illustrates the distribution of the research interests from a sample of 122 articles published in prominent peer-reviewed journals.

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[1] Part of this section has been published in: A. Chatterjee, D. Burmester, A. Brent, and R. Rayudu, "Research Insights and Knowledge Headways for Developing Remote, Off-Grid Microgrids in Developing Countries," Energies, vol. 12, no. 10, p. 2008, May 2019.

Table 1.1. Review of publications for off-grid systems

Publication	Description
[14]	Review of an off-grid system based on the configuration, control strategy, techno-economic analysis, and social effect for a case study in India.
[15]	A 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.
[16]	A general framework for microgrid systems and an extensive analytical review of the literature for stand-alone and hybrid systems.
[17]	A review was 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.
[18]	Review and comparison of the stand-alone solar and hybrid solar systems based on case studies implemented for various locations throughout the world.
[19]–[21]	An overview of the status of clean development mechanism (CDM) portfolio for stakeholders and assessment of potentiality of sustainable energy technologies for Thailand.
[22], [23]	Simulation software tools reviewed for off-grid systems.

Table 1.2. Microgrid technology layout for off-grid systems (Stand-alone and Hybrid Systems)

Publication	Description
[24]–[26]	PV based systems for irrigation and water pumping activities.
[27]–[31]	Technology for energy systems such as street lighting, solar charging stations, and solar charging.
[32]	Review of the various inverter topologies for PV systems in a grid-tied scenario.
[33]	Various configurations for charge controllers with importance on MPPT for PV based systems.
[34], [35]	Typologies of Nano-grids for DC systems with technologies of maximum power point tracking.
[14], [36], [37]	Technology layout for hybrid PV-wind energy system design for essential lighting and mobile phone charging provision purpose.
[38], [39]	Solar smoother techniques for analysis of PV integrated systems and estimation of permissible PV penetration ratio.
[40]	Representation of the system model for rural electrification in Cameroon consisting of a hybrid Wind-diesel battery technology.
[41], [42]	Design and comparison of various hybrid (PV-wind-diesel-battery) configurations of energy systems.
[43]–[47]	Design and layout characteristics of hybrid systems for measuring the fuel consumption and energy productivity.

Table 1.3. Microgrid models and simulation methodologies (Stand-alone and Hybrid Systems)

Publication	Description
[48]	A mathematical model for the performance estimation of wind-driven roto-dynamic pumps varying operating conditions for water pumping applications.
[49]	Simulation-based sizing curves developed for PV-battery and diesel – battery configuration.
[50]	Particle Swarm Optimization Theory model managing water-energy nexus for Nigerian context.
[51], [52]	Incorporation of uncertainties in solar resource and component-based cost determination of energy systems.
[53]–[58]	Mathematical modelling and energy dispatch strategy analysis for a case study analysis from an Indian perspective.
[54], [59]–[62]	A rural India perspective for energy management optimization model for reliability and economic parameters.
[63]	An evolutionary-based algorithm for dispatch strategies based on economic and environmental parameters.
[64]	An expanded transshipment model is proposed for modelling a hybrid power system with energy losses and for capacity estimation and storage requirement analysis.
[65]	A hybrid energy system designed with the incorporation of load shifting and energy storage techniques.
[66]	A probabilistic battery state model developed for evaluation of reliability analysis.

Table 1.4. Microgrid techno-economic analysis (TEA) and case studies for off-grid systems (stand-alone and hybrid)

Publication	Description
[67]–[70]	Typology identification and similar renewable energy system identification technologies in the African context.
[71]–[78]	Standalone microgrid systems with single-source systems globally for various community applications- street lighting, household electrification, and school electrification.
[16], [79], [88], [89], [80]–[87]	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 shaving purpose.
[90], [91], [100], [92]–[99]	Substantial information regarding the off-grid scenarios considering a Nigerian perspective and used as the background study for the present research. However, the system comprises a single source facing intermittency in power generation. The issue correspondence to the fact that the solar energy output can be highly fluctuating with the effects of cloud passing, shading, soiling, and derating factors of PV.
[5], [101], [110]–[119], [102], [120]–[127], [103]–[109]	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 the Asian perspective with an emphasis on electricity provision for houses. The energy access to the developing countries has been the focus of various case studies for system sizes ranging from 0.2-100 kW.

A synthesis of all the reviews as tabulated above has been discussed further in detail:

a) Review of publications for off-grid systems (Table 1.1)

In Table 1.1, a detailed overview of the review publications for off-grid systems has been discussed. The task for referring to review publications was based on the researchers' virtue to analyse focus on off-grid systems for rural electrification, and a purpose to understand the various aspects of the decentralized systems. In order to so, the review paper of Mandelli et all. [16], review of more than 350 papers mainly published from 2000 to 2014 within selected journals. Besides, it describes the role of small-scale generation systems throughout the process of electrification, the main features of rural areas and their typical energy uses. Also, the work results in a comprehensive review which organizes and capitalizes the main fundamentals of the addressed topic and provides elements to get acquainted with the literature. Bhattacharyya et all. [17], developed a comprehensive overview of methodologies to examine technology options for rural electrification. He grouped them according to three classes: techno-economic feasibility, analytical approaches (indicator-based, optimization techniques, multi-criteria decision making, systems analysis approach), and practice-oriented approaches.

The final recommendation is that a hybrid option can complement the strengths and shortcomings of each approach. Table 1.1 focuses the attention on the evolution within the scientific literature arena of methodologies towards the development of multi-criteria and multi-objective approaches which are capable better to address multiple benefits and sustainability in electric supply planning. Sinha and Chandel [22], and Connolly et al. [23] analysed respectively 19 and 37 software tools for hybrid RE systems. Sinha and Chandel concluded that HOMER is the most widely used tool due to its completeness. Connolly et al. found evidence no tool addresses all issues: the ideal tool is dependent on the objectives that must be fulfilled.

b) Microgrid technology layout for off-grid systems (Table 1.2)

Referring to the category in Table 1.2, it can be observed that PV is the most investigated technology, ranging from the smallest solar home systems (some Watts) up to the biggest community systems for water pumping as in [24-26]. The interest in different layout of the systems follows the PV technologies, which are generally analysed together with other specific characteristics. For example, Chaurey and Kandpal [29], provides valuable information for solar lighting. Besides Hassan et all [30] provided an overview of the MPPT charge controller for PV- based systems. Also, Diouf and Pode [31], provides a particularly complete analysis of the different components, layouts, and performances of a number solar home system (SHS) systems. The studies addressing bigger systems follow a similar pattern: Jana et all [32] work can be cited as an example of a paper discussing the inverter topologies for single-phase grid-connected PV systems. As per other technologies nanogrid systems, as well as small wind ones, have been described in few studies. In this case, the emphasis is on the development of appropriate solutions for the main system components according to the context, such as using pumps as turbines or locally constructing timber-blades wind turbines.

As per the layout and components of micro-grid systems, the number of selected papers is much smaller compared to the ones referring to stand-alone systems. Moreover, all these publications are quite recent, having been published in the last four years. These two facts could be considered as an index of more recent interest of the literature for this kind of systems, which indeed require a more complex layout and technology. The typical sizes of the investigated systems vary from some kW up to 20 kW. In this case, the most studied technology is small hydropower (SHP): different studies look for the layout definition and the installation methods according to the local context, as well as to the different kind of turbines. Locally manufactured wind systems have been addressed, giving a complete overview of different system configurations and components. Few papers are about hybrid micro-grid systems, and the number of selected papers is slightly higher than the case of single-source micro-grid systems. The size of the systems vary in a wide range, from some kW up to hundreds kW. It is interesting to look at the different systems configurations which different papers addressed. The coupling of a RE technology with a traditional one (PV-diesel) is the simplest typology. A second typology is obtained as an extension of the first one, by adding a storage system (PV- diesel-battery; wind-diesel-battery). Besides, an article presents the case of a system consisting of two diesel generators, a PV array and a battery. Systems are also made up of two RE technologies and a battery, constitute a third group (PV-wind-battery). In addition to this in [41-42], more complex cases constitute a PV- wind-diesel-battery system is compared to other simpler combinations of the same technologies (e.g. PV-diesel-battery).

c) *Microgrid models and simulation methodologies (Table 1.3)*

This section noted in Table 1.3, address the models and methods for the simulation, and sizing of off-grid systems, where, the literature analysis reveals that major attention has been devoted to the optimization of the systems for microgrid systems. The process of the optimization techniques for the systems implied involve various technologies. Nevertheless, crossing the three categories (stand-alone, micro- grid and hybrid micro-grid), a common classification of the optimization of the systems based on simulation and sizing techniques may be recognized. Typically, the process involved can be categorized into three:

- intuitive: This process involved simplified calculations of the system components size based on daily values of required electric load and resource data.
- numerical: This process comprised of several combinations of system components sizes which are simulated typically every year, employing hourly or daily load and resource availability profiles, and one or more objective functions are used to select the best components set.
- analytical: In this process, the mathematical optimization problems with objective functions subjected to one or more conditions were involved. The objective function(s) and the conditions are the physical modelling elements of the system, defined utilizing functional relationships between the component specifications and the economic and technical parameters.

d)Microgrid techno-economic analysis (TEA) and case studies for off-grid systems (Table 1.4)

Most of the selected papers constituting Table 1.4 are characterized by a description of technical design, optimization and economic evaluation of proposed energy systems. Three main categories for most of them can be identified:

- technical design and sizing analyses with comparison among different available technologies,
- economic feasibility analyses with simulation and evaluation of different scenarios; and
- techno-economic feasibility analyses which carry out systems optimization from technical, economic and environmental viewpoints.

During this consideration, it was observed that the majority of the cases considered are in Asia and Africa. For instance, the cases in [67-70] considered typology identification and similar renewable energy system identification technologies in the African context. Besides, the cases in [90-91] provide substantial information regarding the off-grid scenarios considering a Nigerian perspective and used as the background study for the present research. However, in the cases [92-99], the system comprises a single source facing intermittency in power generation. The issue correspondence to the fact that the solar energy output can be highly fluctuating with the effects of cloud passing, shading, soiling, and derating factors of PV. Chatterjee et focused on Indian aspects for decentralized electrification where the discussion-oriented towards ensuring techno-feasibility analysis of rural electrification.

Based on the literature analysis, it is evident that the research activities have focused on individual technologies, or are site-specific, owing to off-grid systems having varied characteristic features with different value propositions for distinctive microgrid segments.

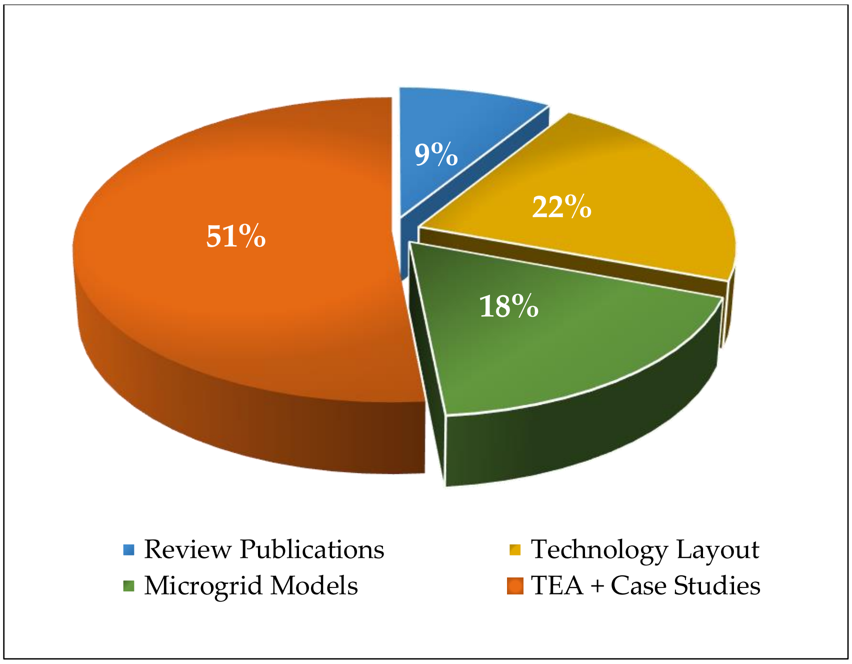


Fig 1.1: The distribution of microgrid research from a sample of 122 research articles

Fig 1.1 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," due to a predominant interest towards a hierarchical preference for household electrification. The hierarchic way has often overlooked holistic access towards other structural typologies (primary school, health centres, community development infrastructure uses) and aspects of rural community developmental needs. The indifference in electricity access adversely affects a comprehensive sustainable development of the remote communities, thereby indicating a need for unified electricity access.

A review of the literature further indicates the lack of a detailed standard framework that considers the cross-sectional evaluation of the long-term sustainability of off-grid, remote electrification systems. In order to resolve the techno-economic challenges of rural electrification systems, an understanding of both successes and the barriers towards sustainable, rural, off-grid systems is essential. Furthermore, the task may result in achieving widespread scaling of the deployment of rural microgrids and provide better insights into the factors influencing the hindrance towards the SDGs. Therefore, understanding the issues responsible for the lack of achieving prolonged sustainable energy access solutions, the research determines the dimensions and the objective of the research presented in the thesis.

1.2 Research Objective

With the identification of the research gaps, it is essential to identify and characterize the overall dimensions of rural electricity services for remote communities in developing countries. In order to achieve this, it is vital to ensure the achievement of universal access to affordable, reliable, and sustainable electricity services. The understanding of the scenario, therefore, lays the foundation of the main objective of the thesis, which is to:

"Establish a conceptual framework to improve the design of remote off-grid microgrid systems through a Techno-Economic Assessment (TEA) approach."

The objective set forth is in accordance with the "Sustainable Development Goal 7" (SDG.7) indicated by the UNDP for "Affordable and Clean energy access." The accomplishment of the objective mentioned above would improve the electricity scenario in the remote communities of the world, improve the electricity crisis, and impact the other SDGs, thereby enabling directions towards the 2030 target of the United Nations. The roadway towards the accomplishment of the objective was, however, dependent on the following tasks:

- Establishing a formative evaluation for developing a research evaluation design,
- Developing questionnaires for research assessments. In this research, the questionnaires were developed to analyse the cases as tabulated in Table 2.1, and not for survey purpose. The purpose for developing questionnaires is to advance knowledge for understanding the limitations of the existing systems and further establish a conceptual framework from lessons learned from the cases; and
- Verifying and further validating the established framework in order to enable the applicability of the improved TEA to maximize long-term sustainability and scaling up the off-grid microgrid systems for remote community electrification in developing countries.

Further, a research strategy has been discussed in the next section to enable understanding of the flow of the tasks set forth to achieve the main objective of the thesis, that of establishing a conceptual framework to improve the design approach for the TEAs.

1.3 Research Strategy

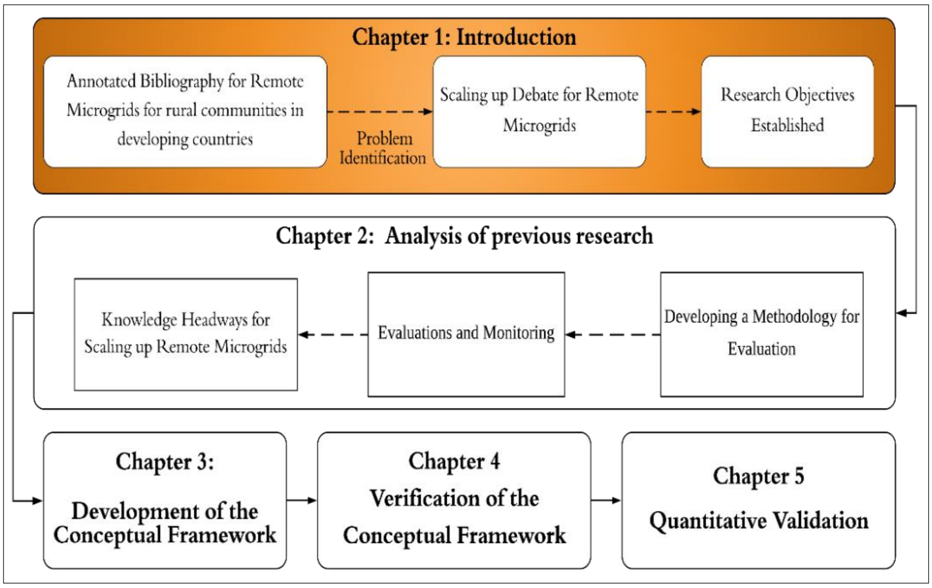


Fig 1.2. The thesis research strategy

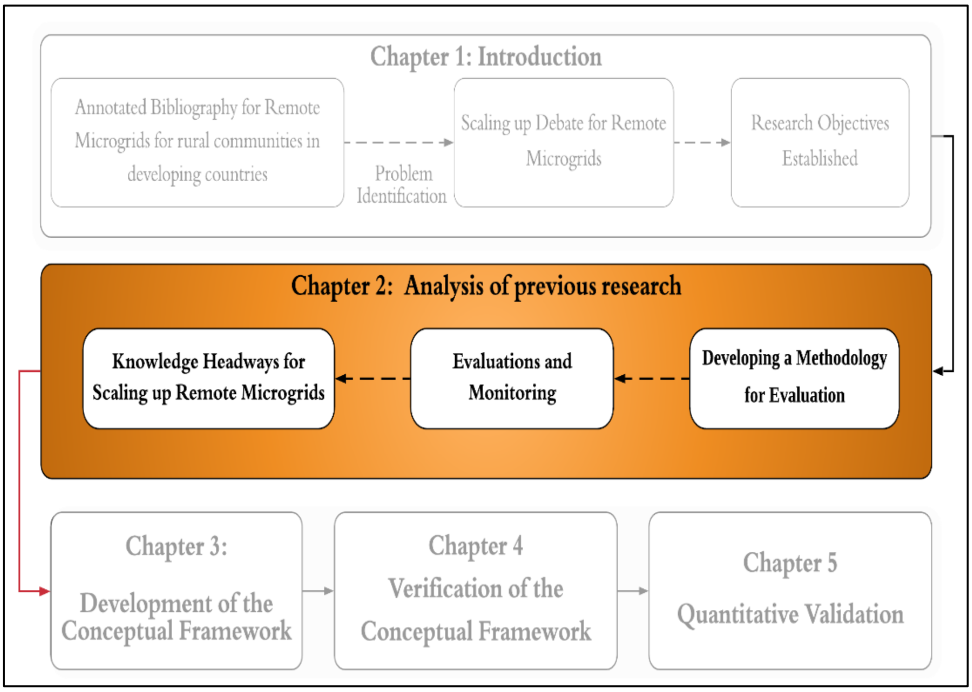
Given the research rationale and the objective of the research set forth, a research strategy was established, as seen in Fig 1.2. The Technology and Policy Assessment (TPA) approach, developed by the UK Energy Research Centre (UKREC), which informs decision-making processes, was adopted for the research. The thesis, based on the TPA approach, followed an annotated literature review for gathering information, determining the dimensions of the study, and establishing the development of evaluation criteria based on identified attributes. The attributes identified could potentially assess the impact and the proper functionality of remote, off-grid microgrid systems. The research evaluated the functional state of off-grid renewable energy systems in the context of rural electricity access in developing countries whose attributes were considered as parameters to assess 19 rural microgrid cases in the Asian and African contexts. The knowledge headways were then formulated, based on lessons learned from the shortcomings highlighted in the evaluated cases, and accordingly, a conceptual framework was established to improve the design of the TEA approach for the remote electrification process.

Furthermore, in order to situate the established conceptual framework, a verification process was undertaken, incorporating a focus group of knowledge expertise in similar research context and interests. The focus group involved two taskforce committees, under the Working Group on Sustainable Energy Systems for Developing Communities (WGSESDC) of the Institute of Electrical and Electronics Engineers (IEEE). Thereafter, to suit the appropriateness of the conceptual framework established, a case study comprising a remote village scenario was considered to validate the improved framework. The validation of the framework can potentially enable decision-makers, energy developers, and practitioners to efficiently maximize sustainable approaches for remote off-grid electrification in the rural communities of developing countries.

Having provided the background to the study, the research objectives as well as the research strategy employed in this study, the next chapter provides an analysis of previous research relevant to the phenomenon under study.

Chapter 2

Analysis of previous research



The previous chapter provided an insight into the rationale and established the objectives of the research, following a theoretical review process. This chapter asserts a qualitative research methodology while employing an integrative review process to confirm the need for further research. An integrative reviewing process is defined as: "*A review method that summarizes past empirical or theoretical literature to provide a more comprehensive understanding of a particular phenomenon or healthcare problem*" [128]. An integrative review, thus, has the potential to inform research practices and policy initiatives review the present state of the art of research, and can further contribute towards theory development, having direct applicability to practices and policy.

The present chapter consists of four sections. The first section explains the research methodology undertaken for the literature analysis, while the subsequent sections follow the analysis and discussions on the adopted methodologies. The chapter also considers systematic reviews of the relevant academic literature and finally concludes with the lessons learned in ways of knowledge management to generate new perspectives for further research developments.

2.1 Research Methodology

The research methodology for the literature analysis constituted a systematic review of both academic studies and grey literature. The intent was to investigate:

- The range of frameworks existing for electrifying remote communities and their corresponding strengths and weaknesses.
- Assessment procedures of the existing frameworks which prioritize a focus on the techno-economic assessments (TEA) for remote off-grid electrification using suitable compilation tools and methodologies; and
- Assessing the adequacy of the attributes in the frameworks for quantitative analysis of the rural microgrid evaluations for their functionality, underpinnings, and success.

The first part of the literature analysis, based on an annotated literature review for gathering information, constitutes the evaluations of remote microgrids in rural communities. It determines the dimensions of the study and informs the development of evaluation criteria based on the identified attributes, having a potential impact on the proper functionality of remote off-grid energy systems. The attributes were considered as parameters to assess nineteen rural microgrid cases in the Asian and African contexts, 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.

The second part of the literature analysis is based on the lessons learned from the failed microgrid cases and informs the need for a standard framework to be developed for maximizing the scaling up and improving the design of the remote microgrids for rural communities. The review further uncovered a handful of evaluations of energy models/ toolkits developed to inform key stakeholders on the renewable energy planning processes and developments. Several techno-economic assessments of the impact of renewable energy projects in developing country contexts, as well as frameworks developed by energy practitioners and academicians for evaluating respective rural renewable energy projects were also revealed through the literature review.

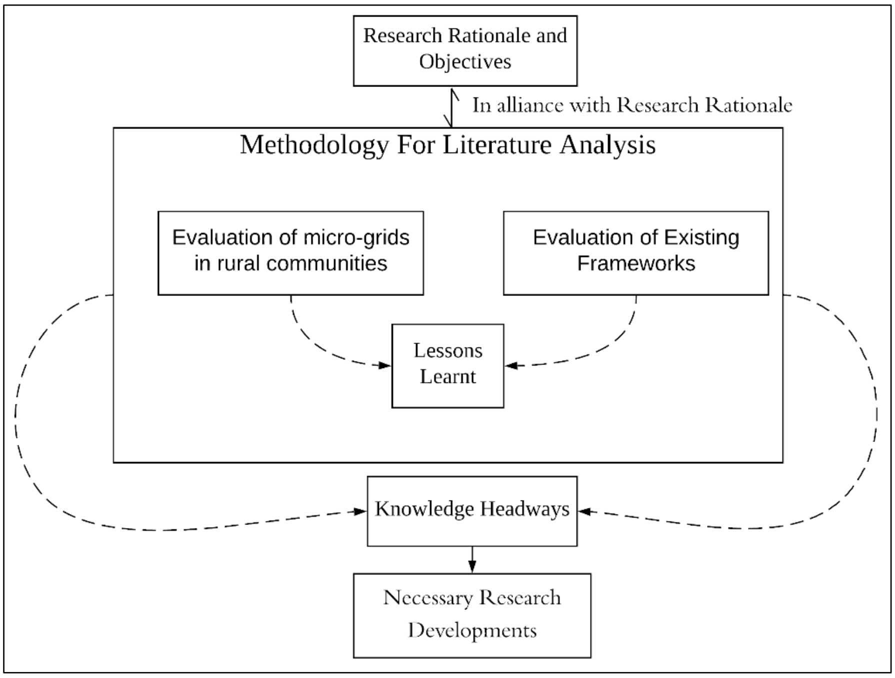


Fig 2.1. The methodology adopted for the analysis

2.2 Evaluation of microgrids in rural communities[2]

It is necessary to define the evaluation criteria or factors used to 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*" [129] to establish attributes that suit an evaluation of the current operational status of microgrids. Several case studies of microgrids for rural communities in

[2] Part of this section has been published in: A. Chatterjee, D. Burmester, A. Brent, and R. Rayudu, "Research Insights and Knowledge Headways for Developing Remote, Off-Grid Microgrids in Developing Countries," Energies, vol. 12, no. 10, p. 2008, May 2019.

developing countries, available in the scientific literature, were used as a basis to define the principles for the evaluation. However, the rural electrification by itself suffers from several criticisms as listed below:

- it ignores the quality of the electricity supply;
- it treats all electricity supplies the same;
- it ignores the reliability and availability of the electricity supply.

The attributes used for the evaluation comprise 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) [130] as the criteria for microgrid evaluations, which are specifically technology-neutral [131] and account for both the on- and off-grid energy systems [132]. The MTF is part of a comprehensive approach to assessing energy access in general, and it considers energy access for household uses (electricity, cooking, and heating). However, this thesis will focus on household electricity use (Appendix VI). The attributes evaluate the energy access (electricity, cooking, and heating) for household, productive activities, and community usage as a holistic approach and not electricity access in specifically.

The decision making and strategy for the MTF focus on a top-down approach model. The model approach evaluates energy access for rural electrification by classifying the energy systems based on Tier levels ranging from Tier 0 to Tier 5, which are, arguably, not adequate for the following two reasons:

- The Tier levels are not confined to any rural context in particular;
- The MTF is technology-oriented, wherein the socio-environmental and economic factors do not form an important aspect of evaluation;
- The MTF lacks essential aspects for considering climate change actions or emphasis on renewable (fossil-free fuel) usage for electricity generation and supply;
- The energy pattern usage and demand in a rural scenario differs from an urban scenario, confining to a lower load factor and uncertain day-to-day random variability; and
- The breakpoints between the tiers in the MTF are arbitrary

These factors highlight a need for a change in paradigm approach to assessing the electricity systems for rural contexts, 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.

In addition to the technical and economic attributes emphasized 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 broader community and 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.

As such, the microgrids must cater to the community's needs, which can be electrified, and that evolve. This requires a change in paradigm concerning microgrid utilization, evaluation as well as, application, and is the domain of resilience assessment, which should form part of the energy systems' design processes. To overcome the inadequacy of the MTF, to be directly used for rural microgrid evaluations, to consider the social and developmental aspects, and to direct future research efforts for remote microgrids, the study used two additional attributes, termed as "Legality" and "Sustainability," as essential for evaluating the remote microgrids. "Legality" refers to challenges arising from lack of proper regulatory enforcements for rural electricity infrastructures and projects on the one hand. "Sustainability," on the other hand, refers to an energy approach involving only renewable energy sources for electricity generation in remote locations of the developing nations. In other words, "Sustainability" has to do with microgrid systems that do not require the purchasing of fossil fuels. The attributes are then described as follows, with the means to assess each:

- Capacity: The demand-supply matching of electrical energy is an essential factor in the process of designing a power system [133]. The capacity of a microgrid 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 using two scales, where 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 the rural electrification system, whereas the second scale indicates the social viability and standard of the rural community.

  As it were, a steady increase, in both the scales, could lead to different consequences, and thus, 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 could 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 an 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 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?

o 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 rural communities, electricity access is prioritized in the daytime for agricultural chores and varied cottage industries, with evening access of the electricity to the households and communities being evaded. The evening supply of electricity is vital 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 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 as follows:

- (AvQ1) At the supplier end, what is the energy utilization 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 microgrid, generally considered as the "willingness to pay" from a consumer's perspective [134]. However, the meaning of the term is often misinterpreted, primarily when used to discuss the affordability of the system from a developers' perspective in order to compensate for the operational and replacement costs that are incurred during the overall lifetime of the project. At the consumer's end, the "willingness to pay" is an indicator relating to the annual income of the respondent and reflects the socio-economic aspect of the consumers involved in the community project. From the developer's end, the attribute of affordability at developers' end, can be extended to help understand the nature of the project in adapting itself to project expansions at the end of the project lifetime of a microgrid, which is supposedly 25 years. Affordability also helps in understanding the flexibility in terms of costs incurred during the operational stage of the project for component replacement purposes, thereby reflecting on the foundation of the techno-economic aspects of the microgrid 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 of paying 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 interruptions resulting from natural phenomena, such as days of less sunshine, excessive winds, or natural disasters, such as earthquakes and floods. The microgrids are, therefore, 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 microgrid?

- Legality: This evaluation attribute in the context of developing countries corresponds to the barriers to the microgrid 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 concerning the legality attribute:

- (LQ1) Are the ownership structure and institutional support of the microgrid system clearly defined?
- (LQ2) Are supporting policy guidelines available, efficient for the deployment, and successful functionality of the microgrid project?

- Sustainability: Another critical aspect that needs attention for the evaluation of the rural microgrids 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 to electricity can lead to accomplishing a holistic approach towards the SDGs. The attribute "Sustainability" is thus confined to assess the utilization of renewable energy sources only for electricity generation. The evaluation aspect can be utilized to access the sustainability of the project at the design stage of the project with life cycle assessments, during the operational stage of the project, and at the end of the project lifetime, by defining a proper disposal procedure of the system components. The two critical questions to be asked here are:

  - (SQ1) Is the microgrid 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?

2.3 Research analysis based on the CAARLS attributes[3]

As stated in [135], "data on reasons for microgrid's 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 contains enough generalized advice on best practices and user-centric approaches. The literature, however, lacks in terms of the approach of electrification project developments in geographic constraint locations. Also, the literature lacks in enumerating 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.

A report, published by the United Nations Foundations [136], 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,

[3] Part of this section has been published in: A. Chatterjee, D. Burmester, A. Brent, and R. Rayudu, "Research Insights and Knowledge Headways for Developing Remote, Off-Grid Microgrids in Developing Countries," Energies, vol. 12, no. 10, p. 2008, May 2019.

are based on personal interviews and surveys and was found appropriate for the study, considering a blend of the techno-socio-economic details, essential for analyzing the microgrid challenges based on the evaluation attributes. As such, instead of capturing a full 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 dearth communities. The remaining case studies selected for the analysis of the research were identified using the "Advanced search" option available in Google Scholar, thereby identifying 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 for detailed case studies, with similar demographics and electricity issues for rural communities outlined by the IEEE Working Group on Sustainable Energy Systems for Developing Communities (IEEE SESDC) [137]. The cases that have been considered for this study constitute a mix of theoretical/planned and implemented microgrid projects.

Table 2.1 summarizes the 19 case studies and the corresponding levels of compliance with the attributes of the CAARLS. The contrast of the colours based on the questions developed for each attribute by the researcher in the thesis determines the level of the barriers affecting the microgrids. The levels have been categorized into high barrier levels in red, low barrier level in blue, low success level in green, and yellow for cases where enough information was not available.

Table 2.1: 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 [138]	PF	X	X	X	X	X	✓
	OREDA, India [138]	PF	X	X	X	X	X	✓
	WBREDA, Sagar Island , India [138]	NF	X	X	✓	✓	X	✓
	Desi Power, India [138]	F	X	X	✓	X	X	✓
	Mera Gao Power, India [139]	F	X	X	✓	X	X	✓
	Husk Power System, India [138]	F	X	X	X	✓	X	✓
	UREDA, India [139]	PF	X	✓	✓	✓	✓	✓
	Gram Oorja, India [139]	PF	X	✓	✓	X	✓	✓
	Green Empowerment/Tonibun g/Pacos (GE/T/P), Malaysia [138]	PF	✓	X	X	X	X	X
	Electricity of Haiti (EDH), Haiti [138]	NF	✓	✓	X	✓	✓	X

	South Africa, [140]		X	X	X	X	X	X
Literature Based Case Studies	Nigeria [92]	NI	X	X	NA	X	X	X
	Pakistan [141]	NI	NA	X	NA	X	X	X
	Bangladesh [142]	NI	X	X	NA	X	X	X
	Bangladesh [143]	NI	X	X	NA	X	X	X
	Bangladesh [144]	NI	X	X	NA	X	X	X
	Kenya [145]	NI	X	X	NA	X	X	X
	Nigeria [146]	NI	X	X	NA	X	X	X

Where,

High Barrier Level	(red)
Low Barrier Level	(blue)
Low Success Level	(green)
Not Applicable	(yellow)

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 Partial Functional, NF= Implemented and Non-Functional, NI= Not Implemented, NA= Information Not Available

From a capacity perspective, the questions CQ1 and CQ2 were used to assess the cases. For instance, whether the community participated in the load estimation during the design phase of the electricity system. Also, the extent to which energy-efficient practices considered. However, the assessment result reveals that a microgrid may satisfy the basic design model to supply electricity for 4-6 hours during the daytime but fails to cater to the needs for the evening hours of electricity provisions, which the associate community may require. The feature of the microgrid providing electricity only during the daytime indicates an inadequacy in the pre-assessment stages of its 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 critical changes/variations that affect the system operational cost and functionality over the lifetime owing to, for example, changes in the fuel cost or degradation of the components.

Also, the assessment revealed microgrids comprising 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), and which affects the "willingness to pay" factor among the village dwellers. A lower customer satisfaction level for electricity availability may lead to payment disputes, resulting in poor revenue collection for the energy supplier. Lower cost recovery from the microgrid projects compels the nodal agencies to limit their services for maintenance and replacements of faulty components. Here, 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 essential 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 behavioural aspect of the users in the community towards this attribute for the microgrid systems.

From a reliability perspective, 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 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. It is also the case that an inefficient energy utilization of some of the systems, in addition to inadequate management of the electricity supply at the user end, often leads to system disruptions and prolonged system failures. A few cases indicated disruptions in electricity supply lasting over a month due to natural and climatic catastrophes, and the challenge for the systems to gain full operational status, thereby highlighting a significant 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 significant 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.

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 entirely relied on diesel generators. The theoretical cases available in the academic literature reviewed, indicate design parameters for the system diverging from using 100% renewable energy resources to serve the peak load demands. The cases also demonstrate a failure to more efficient energy usage patterns among the communities.

The evaluation also highlighted the dynamic interaction between attributes. Fig 2.2 provides an example of the dynamicity of the attribute “Legality”, 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.

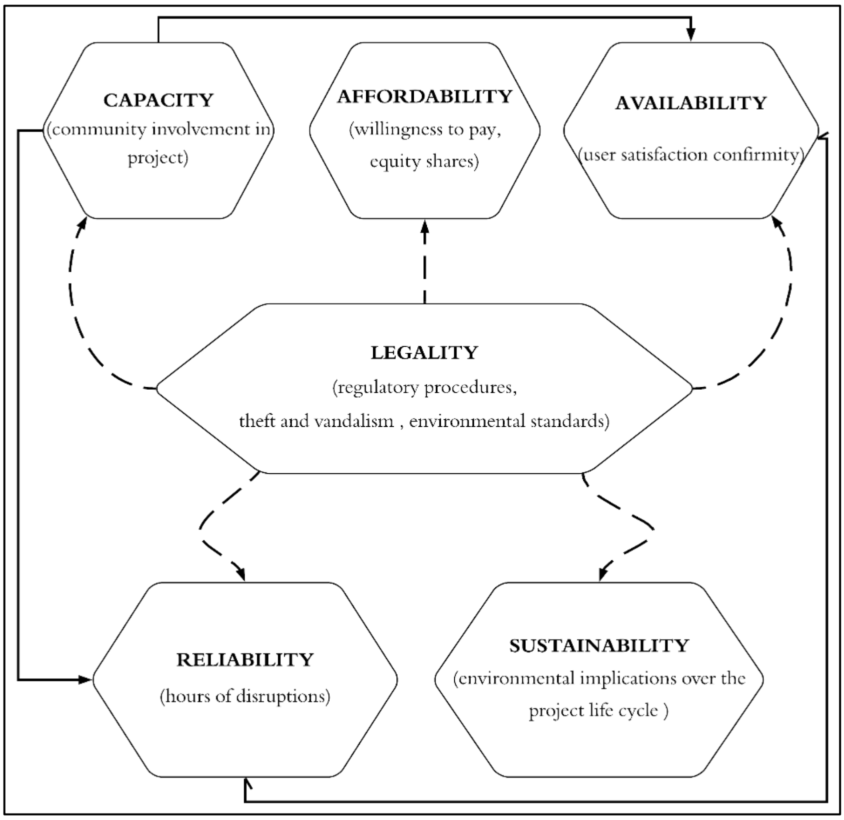


Fig 2.2: Relationship diagram of the CAARLS attributes

2.4 Evaluation of Existing Frameworks

Several studies conducted in different contexts were evaluated in line with the tasks outlined towards the achievement of the objective of this research. For instance, the research in [147] catered the need for the social perspectives associated with remote energy systems in ways of a classical technical approach in a comprehensive review of existing single- and multi-criteria models. The research extensively highlights the limitations within the context of rural energy planning in developing countries. Here, fifteen tools, including, HOMER, MARKAL, VIPOR, and LEAP, which are predominantly quantitative, were compared.

In another research, the author points out that the traditional energy models are too heavily focused on technical criteria, such as emphasizing the cost of the technology and the cost of power output. Many of the existing models allow the local population to participate only after experts have considered technical decisions [148]. The tools fail to adequately consider the long-term sustainability of the infrastructure while, neglecting to incorporate social criteria into the models, which reflects the needs of local communities [147].

The importance of incorporating social criteria in energy planning based on an argument states that "all research and modelling tools should rely on methodologies that incorporate the interaction that communities have with the technology." Thus, it can be inferred, if the public attitudes towards the technology are not appropriately addressed, unexpected conflicts surrounding ownership, trust, and locality can emerge, ultimately hindering the success of the project [149].

Other criticisms voiced in the literature on the limitations of energy models in the developing countries contexts argue that at present, only a few energy models account for the political, economic, and social dimensions specific to these contexts [150]. This comment relates to the more general use of energy models rather than those that are specifically related to renewable energy, but they provide invaluable insight.

The research in [150] focuses on the energy models used by the IPCC to develop future scenarios on the global use of energy and the potential impact of climate change. The research argues that the models only incorporate dynamics pertinent to developed countries but, fail to include the range of socio-economic issues in the developing countries. For example, income distribution is negated from the models when forecasting energy demand, which underestimates the energy behaviour that is typically associated with either low- or high-income groups. As it were, energy planning models use GDP per capita as a driver for the energy intensity of activities. However, given that developing countries have such a large informal sector, using GDP is not an adequate criterion to reflect the complexities of the economy. In these contexts, the informal activity includes a whole range of activities that take place in the real world, but that is then not absorbed into the model.

Existing evaluations argue that modelling tools do not adequately take into consideration the range of issues affecting developing countries. The authors are in broad agreement that the tools tend to overemphasize the technological, economic, and environmental dimensions to energy planning. They argue that many of the tools overlook the importance of participatory involvement of local communities.

Notably, the evaluations focus on whether the tool itself is accurate and comprehensive and reflects the potential barriers that exist in deploying renewable energy in developing countries. The evaluations point out specific areas where the tools fail on various counts, such as political barriers, policy regulations, and tendering procedures. However, none of the evaluations identified to assess whether renewable energy toolkits, as decision-making tools, are useful for developing countries to achieve their renewable energy aims. As such, the evaluations do not question whether local practitioners use them or find them useful. The evaluations do not entirely consider how the tool (and information) is distributed, accessed, received, read, understood, and used. Nevertheless, these practical issues influence the extent to which toolkits can drive renewable energy deployment.

The exception to this criticism is a study that compares the use of two renewable energy tools in South Africa. Brent and Kruger (2009) compared the SURE-DSS tool to a manual produced by the Intermediate Technology Development Group, which is also focused on rural energy in developing countries and assessed their impact in South Africa. Interviews were conducted with various renewable energy stakeholders in South Africa. The results from the research indicate that the two tools/frameworks were relatively comprehensive and were widely accepted as addressing many of the critical issues highlighted in authoritative studies on rural energy development. What emerged, however, is that many of the responses of the people interviewed were very carefully in line with what was being propagated in the literature. Whether the people interviewed were representative of the people the toolkit was trying to influence needs to be questioned; the people who were being interviewed typically worked in international agencies (and were also likely to be developing such tools or to be familiar with such concepts) but there may not have been many other local stakeholders whose views were not canvassed.

The existing models evaluate the renewable energy frameworks for their accuracy and completeness for sufficiently addressing the techno-economic barriers to deploy renewable energy systems. As such, the approach constitutes the first step of our framework. It is evident that in order to evaluate existing frameworks in ways of renewable energy toolkits, both the content and the concept needs to be addressed. This thesis, therefore, evaluates the current frameworks for their accuracy and integrity, to further enhance a sustainable rural electrification approach, in order to meet the guidelines, set aside by the UNDP to accomplish the SEforALL.

A total of nine toolkits were selected for evaluation for this study, as shown in Table 2.2. The justification in selecting the pool of nine toolkits was two-fold; firstly, to identify toolkits that were produced by major actors that fund renewable energy activities; and secondly, to select a sample of toolkits that represented a wide variety in format, producer, and content. Furthermore, a focus was placed on selecting toolkits that are interactive and in a format that allows for the information provided to be continuously updated in the portals or online databases. As such, static reports that have become or could easily become outdated have been automatically excluded from the toolkit samples.

Table 2.2. List of toolkits and identification of barriers in toolkits

Toolkit Name	Organisation/Sponsoring Organization Developed By	Barriers			
		Economic	Technology	Institutional	Socio-Cultural
World Bank Renewable Energy	World Bank	✓	✓	✓	X
Renewable energy policies database	IEA and IRENA	✓	X	✓	X
Low Emission Development Strategies (LEDS)	USAID and NREL	✓	✓	✓	X
Clean Energy Ministerial	Clean Energy Solutions	✓	✓	X	X
Future Policy FITS toolkit	World Future Councils	✓	X	✓	✓
Energy toolbox	USAID	✓	✓	✓	X
HEDON	Household Energy Network	✓	X	X	X
REEGLE	REEEP & REN 21	✓	X	✓	X
CDKN Network	CDKN	✓	X	✓	X

The evaluation of toolkits in Table 2.2 indicated that the USAID, World Bank, and REEGLE toolkits take a comprehensive approach to policies by covering most of the relevant policy categories. While these toolkits do make a note of many types of relevant policies, they do not go into extensive detail about how individual policies may be relevant to a specific case. The LEDS toolkit is focused on providing links to relevant policies rather than providing their materials on individual issues.

An in-depth analysis illustrates that the toolkits do provide extensive amounts of information on a range of approaches for the energy access provisions. However, the toolkits do not provide the user with selection criteria for technologies to address the issue of darkness prevailing in the rural communities and promoting renewable energy-based systems for electricity provisions.

Most developing countries are well endowed with potential renewable energy sources, and unlike most industrialized countries, there remain vast areas of unused resources to be judiciously adapted for the eradication of electrification issues. Nevertheless, the evaluation of the toolkits indicates that several techno-socio-economic barriers still exist for developing countries with the design, selection, use, and maintenance of renewable energy technology.

Arguably, there is inadequate scientific data on the potential for specific countries, which has often resulted in the selection of incorrect technology and, consequently, generation of inaccurate initial project assessment reports for the establishments of energy systems in a country or region. The dearth of technical knowledge and capacity has led to the distribution of inferior quality technologies, and several of them going out of operation shortly after installation. For instance, worldwide, it is estimated that 10-20% of solar home systems are no longer operational because they were installed without charge controllers and inadequate battery systems [151].

Several practitioners working in developing countries have emphasized the importance of the quality of technology products, where, the renewable energy projects should specify the minimum standards for the equipment, and tests/monitoring should be undertaken to confirm the equipment meeting these standards [152]–[154]. Without a standard of codes and certification, the product quality and acceptability is affected in that low-quality products increase the purchase and commercial risks associated with renewables [155]. However, the quality of renewable energy equipment alone does not ensure that the system will not fail. Proper management and training of the engineers as well as practitioners on the ground are necessary for them to design, install, and maintain the energy systems [156], [157].

The major toolkits, including the World Bank, LEDS, USAID toolbox, and Hendon Toolkits, provide how-to guides on implementing specific technologies. The World Bank toolkit has a designated technology section providing overviews of the major renewable energy technologies, including wind, village hydro, photovoltaics, and biomass. The toolkit also provides guidelines as well as technical and safety requirements for different technologies, which, as mentioned above, has been documented as a critical barrier.

However, none of the above toolkits provides advice on how to obtain data on potential renewable energy resources in specific countries. To the best of our knowledge, the most comprehensive step-by-step toolkit that enables countries to conduct resource assessments is the Geospatial Toolkit, which is an NREL-developed, map-based software application that incorporates resource data and other geographic information systems date for integrated resource assessment. The NREL has specifically developed individual biomass, wind, and solar resource assessment tools and thus far has conducted resource assessments for several developing countries, including Bhutan, Pakistan, and India [158]. Two toolkits, namely LEDS and REEGLE can help guide individual countries on what technologies have worked or what information exists in the country, as they are organized in such a way that information can be retrieved according to country/region.

Several of the toolkits provide high-level overviews of the different renewable energy technologies to help inform policymakers and other stakeholders based on how they function. Nevertheless, they do not resolve a vital issue that developing countries face: the lack of trained staff with the capacity to maintain the equipment. Thus, the toolkits are not focused on delivering step-by-step guidance on developing and scaling up a sustainable techno-economic rural electrification system for remote communities. Institutional barriers include weak (or lack of) legal frameworks for independent power producers and an absence of credible regulatory and monitoring structures. As such, robust institutions are invaluable for providing transparent and predictable signals to customers and industry to generate confidence in renewables.

Based on the detailed evaluations, it could be stated that all of the toolkits address to some extent, the institutional barriers. For instance, the USAID Toolbox has a dedicated section on implementing electricity sector reforms. However, when looked at in-depth, it is merely a presentation on the topic that outlines some of the critical components of the process. Similarly, the World Bank and REEGLE toolkits provide access to documents that touch on institutional reform but lack the ranking system of the documents or guidance to know where to begin. The LEDS tool is unique in that it allows the user to walk themselves through the various steps of implementing the process of transition to a low carbon energy system while evaluating the private and public sector capacity to implement a low-carbon strategy. It is, however, the case that while the toolkits can provide some information on the processes, they are unlikely to provide adequate support for strengthening the institutional capacity in practice.

According to the classification, only LEDS, REEGLE, and the FIT toolkit are structured in such a way as to potentially address the cultural barriers that exist to deploying renewable energy because they allow for some interaction and a mechanism to adapt the information to specific contexts and situations. LEDS and the FIT toolkit allow local policymakers to carry out self-diagnostics to identify the kinds of policies and areas of reform required. As such, they help the user identify what kind of information and assistance is required for their specific circumstances on the one hand. REEGLE, on the other hand, organizes information according to country and enables policymakers to assess what kind of work and information on their specific country exists already. Cultural barriers to renewables can be termed as a result of an inappropriate policy and technology mix being selected that is not compatible with the social nuances of society.

It can be acknowledged that no toolkit will be able to provide a universally applicable solution. However, the toolkits could benefit from a mechanism that enables a country to conduct a self-diagnostic to assess what kind of technologies and policies could be applicable. The LEDS toolkit is the most comprehensive diagnostic toolkit that walks local policymakers through the entire process of developing a 'Low Emissions Development Strategy.' LEDS was developed to help countries organize the process, assess the current situations, and analyse different options in order to prioritize actions. The toolkit is organized in such a way that it compiles the various resources and existing renewable energy tools while organizing them according to what phase of the 'LEDS Process' the country is in. Similarly, the FIT tool, limited to focusing on the design of a feed-in tariff, supports the country through the process, starting with assessing applicability to the country's existing situation. Although it does not explicitly provide a self-diagnostic, REEGLE organizes information in such a way that it is accessible by country and region. This enables stakeholders to assess what policies and frameworks already exist in their country, look at what neighbouring or comparable countries have established, and access resources on topics of interest.

2.5 Chapter Summary and Knowledge Headways

The lessons learnt from the chapter can be categorized in two ways:

Evaluation of the microgrids in rural communities

- The systems fail to qualify aspects based on attributes
- There are practically no provisions for restarting stalled systems
- The existing shortfalls in the MTF
  - Only considered for household purposes.
  - The framework constitutes of energy access as a whole rather than electricity access.
  - The Tier levels lack of exclusiveness for rural scenario in particular.
  - Difference existing in electricity usage and demand pattern in a rural and urban scenario.
  - Technology oriented- Socio-environmental and economic factors not considered.
  - Lack in scope of legality aspect attribute.
  - Arbitrary breakpoints exist between the tiers.
  - Lack of a strategy for escalating microgrid deployment for rural electrification.

<u>Evaluation of the existing toolkits</u>

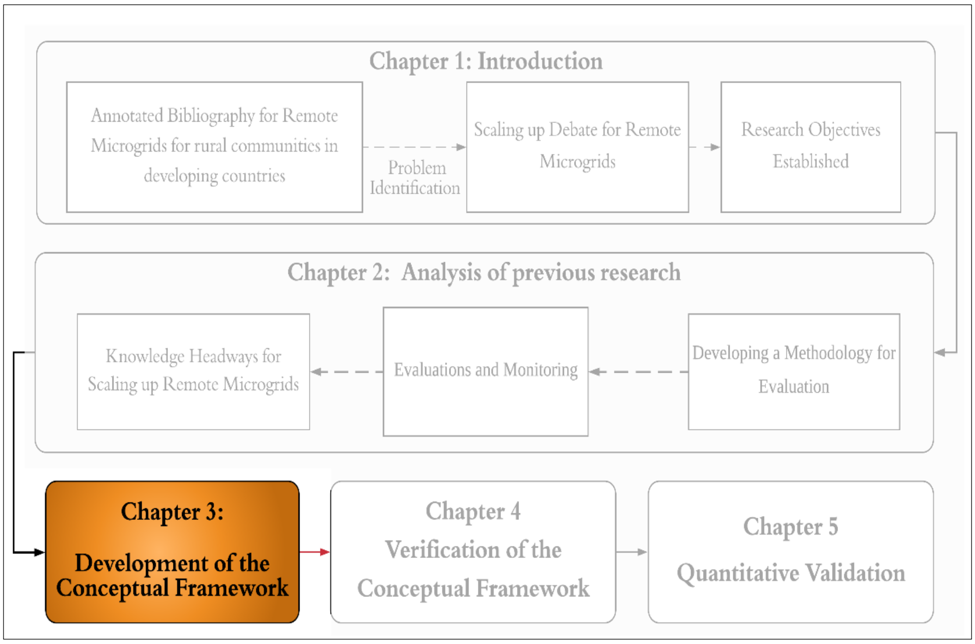
- Energy models are heavily focused on technical criteria
- Fail to adequately consider the long-term sustainability
- Barriers exists with the design, selection, use, and maintenance, training of renewable energy technology
- Lack of step-by-step guidance on developing and scaling up a sustainable rural electrification system

A large variety of renewable energy toolkits exist that provide extensive information on the economic and financial, institutional, social, and technological dimensions to renewable energy. Specifically, copious amounts of information exist on the various policy measures associated with deploying renewables. However, as illustrated by the reviews undertaken in this study, the barriers to renewables in developing countries are not a result of the lack of available policy and technology options but about knowing which ones to select and predict their interaction with the techno-socio-economic issues. Although the toolkits provide broad coverage of technology issues, they do not address how to develop on the ground technical capacity, which is essential to maintain the RET systems.

Existing frameworks in the form of toolkits contain a substantial amount of information. They can be of vital importance to developing more comprehensive and accurate frameworks that seek to address, in further detail, the techno-socio-economic dimensions that align with remote electrification. As such, the issue is not more information, instead how frameworks are organized, and the lack of adapting this to specific circumstances. In order to address this shortcoming, a conceptual framework needs to be established to provide a solution to remote off-grid rural electrification issues and address the barriers, as they can manifest themselves in practice, and not just in theory.

Chapter 3

Development of the Conceptual Framework



The preceding chapter provided an analysis of the current practices and existing frameworks, thereby informing the need for improving the design practices/approaches for microgrid systems in remote communities. In aid of this, the present chapter proposes a conceptual framework (CF) to improve designing practices for off-grid renewable energy systems for remote communities in developing countries.

3.1 Defining "Conceptual Framework"

A CF is a structure that the researcher believes can best define the concepts of the phenomenon studied [159]. It is linked with the perceptions, factual research and legal theories used in promoting and systemizing the body of knowledge [160]. As such, a CF describes the accord between the main concepts and presents an integrated way of analysing the problem that is studied [160], [161]. A CF is logically structured, can be graphical or in a narrative form showing the key variables or constructs and the presumed relationships between them. It is defined as "primarily a conception or model/a tentative theory of the phenomena to be investigated, and the function of this theory is providing information to the rest of the design features to assess and refine research goals, thereby, developing realistic and relevant research questions, selecting appropriate research strategies, and identifying potential validity to a research" [159], [162].

In this thesis, a CF is defined as "a set of logical structures and instructions developed and adopted for an epistemic approach to the design of sustainable microgrids in developing countries."

3.2 Strategy for Constructing the Conceptual Framework

As evident from the literature, the process for building a CF is an intensive process involving theorization and iteration, which requires a constant comparison and movement across various levels of data/concepts [163]. This continuous interplay of the data collection, ideas and concepts are required to control the scope of the emerging theory [164]. As such, the following tasks were undertaken to construct the CF for improving the design of rural microgrids:

- Data Mapping – The first task mapped the spectrum of multidisciplinary literature regarding the access to affordable and clean energy in off-grid communities of developing countries. The process comprised of the identification of text types and data sources, such as existing empirical data and practices. It involved an extensive review of the multidisciplinary texts as well as initial interviews with practitioners, specialists and scholars with a similar research focus, ensuring its validity [165].

- Data Categorization – This task categorized the collected data by disciplinary classification and significance, based on the selection of the on/off-grid microgrid cases, single/hybrid energy sources and the implication for energy projects. The task effectively maximizes the performance of an inquiry and ensures adequate representation of each discipline.

- Concepts Identification – This task allowed concepts to emerge from the literature through a process of "qualitative inquiry that commences with the concept, rather than the phenomenon itself, is subject to violating the tenet of induction, thus is exposed to particular threats of invalidity." [159]. As such, this task led to the naming of the modules for the CF and classifying the activities within each module.

- Concepts Categorizations – This task deconstructed each concept to identify its primary attributes, characteristics, assumptions and role; and, subsequently, organizing and categorizing the ideas according to their features and respective methodological functions.

- Concepts Integration – This task integrated the concepts having similarities to one new idea, thereby reducing the CF to a reasonable number of concepts. For instance, a module that was considered to have a retrospective approach was aligned with another module comprising similar activities.

- Concepts Synthesis – This task synthesized the concepts into the CF in an iterative process that included repetitive synthesis and re-synthesis until the researcher recognized a general theoretical framework that made sense. As stated in [159], researchers using qualitative methods "need to know how they are constructing 'theory' as analysis proceeds, because that construction will … inevitably influence and constrain data collection, data reduction, and the drawing and verification of conclusions". The synthesis also included the verification of the constructed CF, which is the focus of Chapter 4.

- Concepts Validation – This task investigated the credibility of the CF by undertaking a quantitative application of some of the concepts/modules. Chapter 5 discusses the validation process in detail.

- Rethinking the Framework – A theory or a CF representing a multidisciplinary phenomenon is dynamic and allows scope for further revisions/improvisations according to new insights, comments, literature, as well as scientific developments and innovations. The outcomes of the synthesis/verification and validation tasks, thus, informed the amendment of the CF.

3.3 Conceptual Framework for the design of sustainable microgrids

The main objective of the CF is to facilitate the design of sustainable off-grid electricity in remote communities of developing countries. Fig 3.1 illustrates the convergence of the elements associated with the CF that would lead to the attainment of an overall sustainable approach.

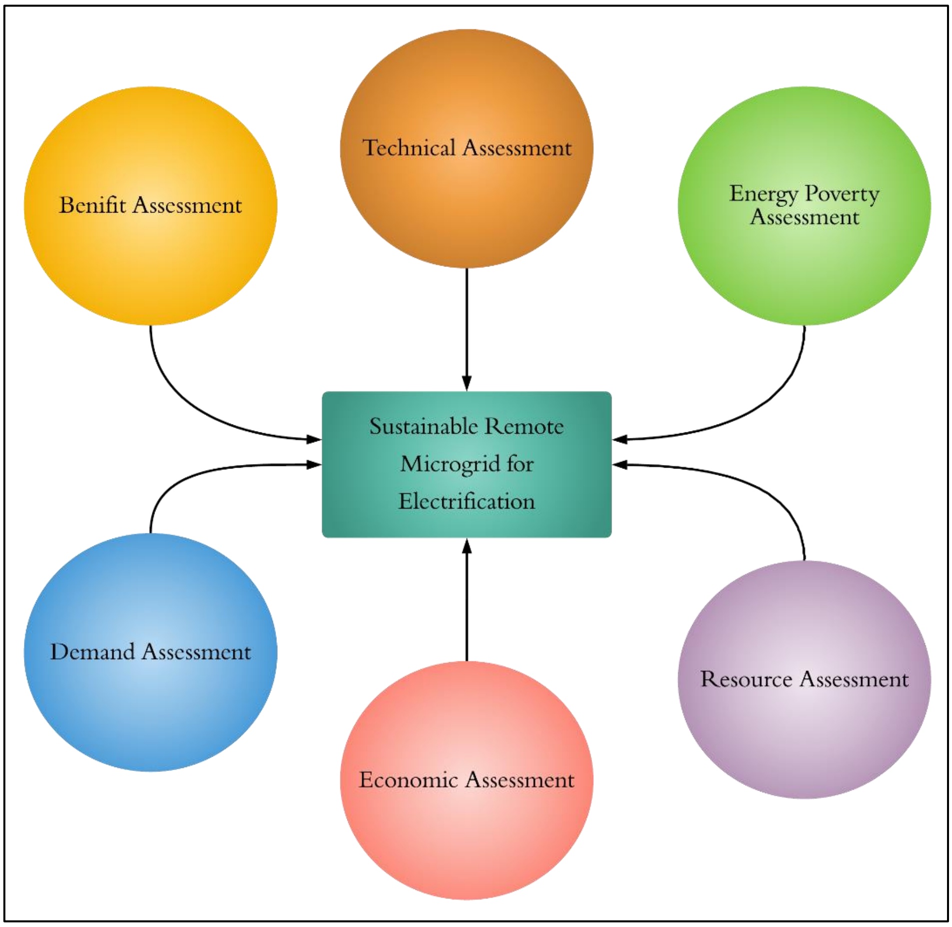


Fig 3.1: Elements convergence for a sustainable microgrid approach

The proposed CF has several features that are distinct from traditional electricity and energy planning frameworks as follows:

- First, unlike the conventional energy planning and electrification frameworks, the proposed framework **focuses on social inclusiveness (stakeholder participation)** and considers the **ability of even the poorest households to gain access** to electricity to meet their basic energy needs for lighting.

- Second, the framework **assesses the financial implications** for **cost-effective options for supplying clean electricity** (fossil-free fuel sources) to consumers.

- Third, the framework **ensures the sustainability, reliability and acceptance of renewable energy options** in order to ensure the quality of energy access programs at the local levels/communities.

- Fourth, the framework **focuses on essential aspects of energy management** as well as benefits of energy access programs for improving the overall social well-being and environmental quality, climate change mitigation, low carbon society, reduction in gender inequality, and other relatable SDGs.

The proposed CF was developed following the indicators of the SDGs, as identified by the United Nations Development Program (UNDP)[4]. The purpose of adhering to the SDGs, lies in achieving

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[4] https://www.undp.org/content/undp/en/home.html

overall techno-socio-economic development of a remote community, by promoting off-grids remote microgrids for affordable and clean electricity access. The CF established follows varied phases, as illustrated in Fig 3.2, which focus on microgrid systems that do not require the purchasing of fossil fuels for electricity access (SDG 7). Also, the CF focus on improving the community participation in the project establishments and functionalities (SDG 8, SDG 17, SDG 11 and SDG 12), as well as an overall approach towards climate change action and life on land (SDG 13 and SDG 15).

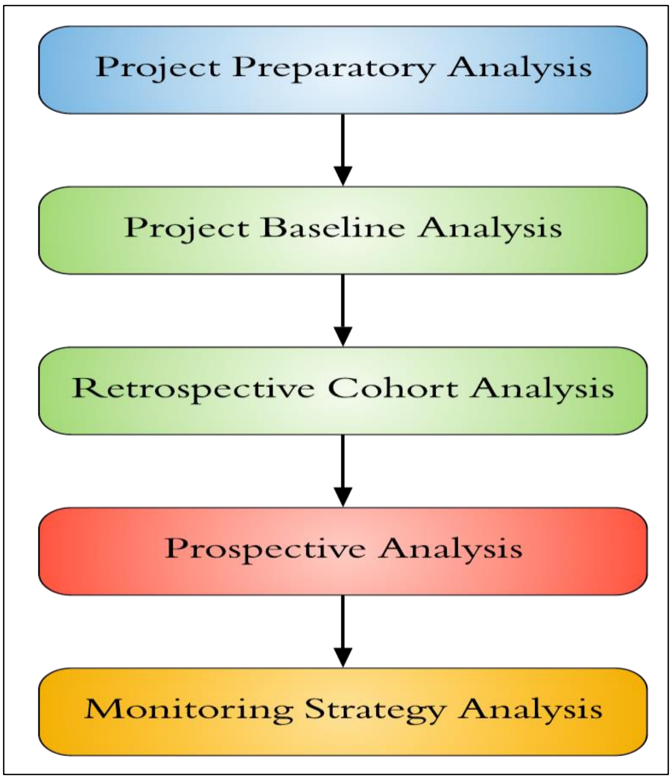


Fig 3.2: Process flow for preparing the CF

Given the importance of microgrids for rural communities, Fig 3.3 illustrates a CF developed to improve the design process that would enable sustainable off-grid microgrid systems for remote/island communities in the developing countries.

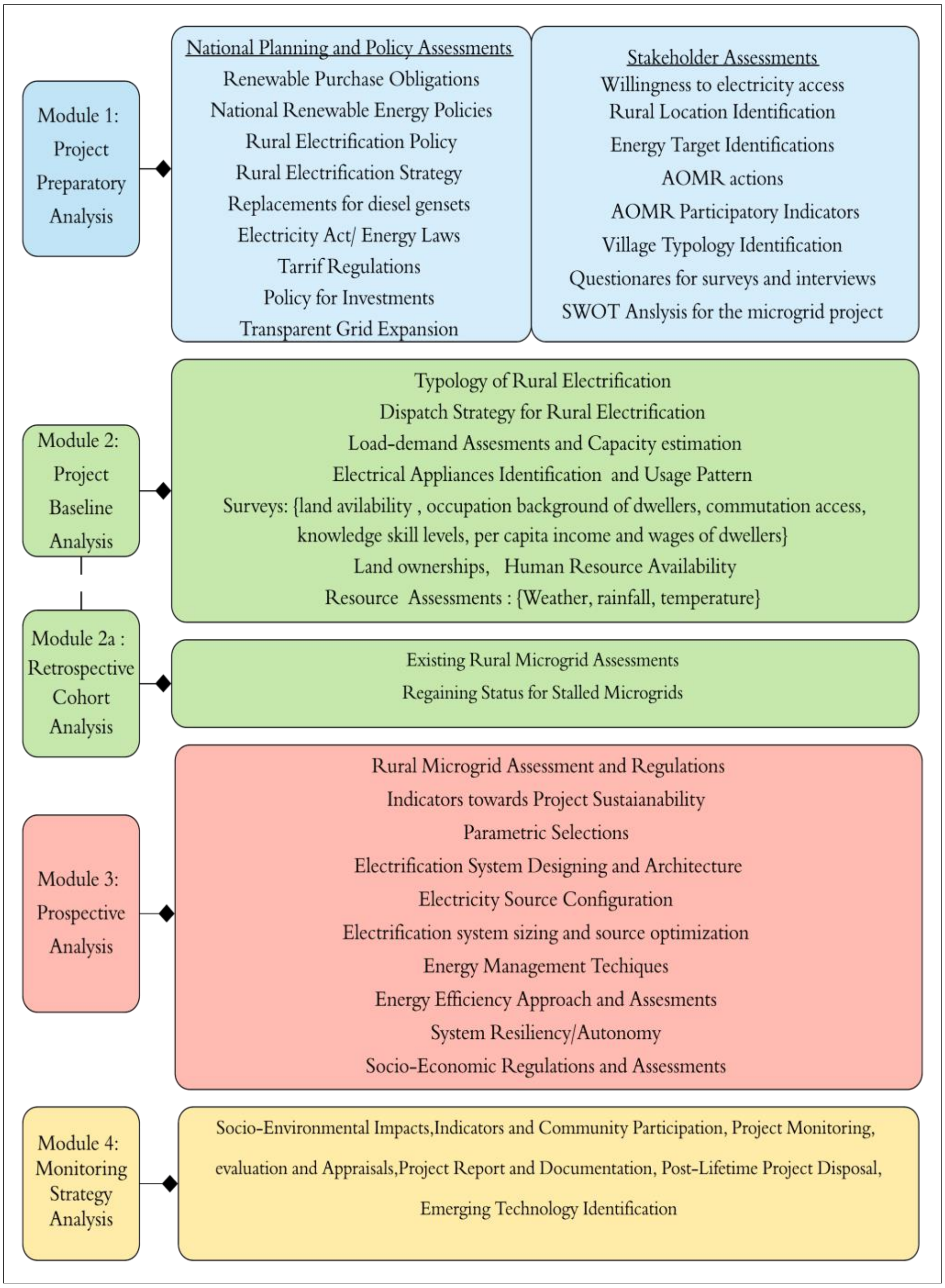
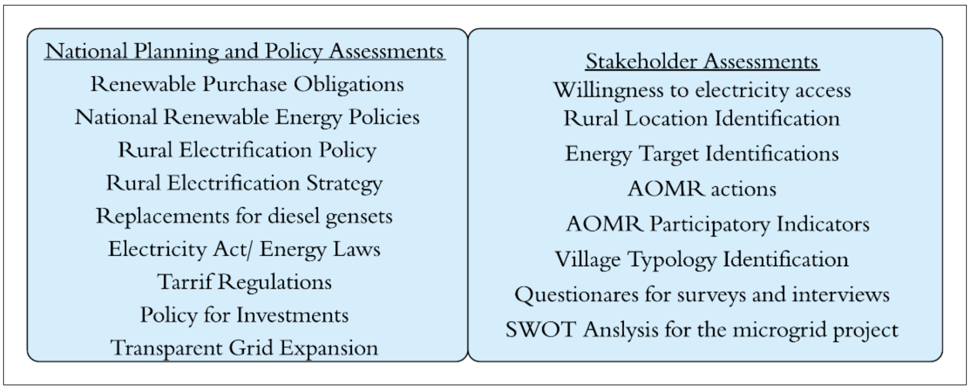


Fig 3.3: Modules and Detailing of the established Conceptual Framework

3.3.1 Module 1: Project Preparatory Analysis



Module 1 is the bedrock for a microgrid project, constituting the assessments for national policies and stakeholder participation. National governmental plans and policies are an integral part of integrating mini-grids into their rural electrification planning and procedures for acquiring uniform electricity access. The central committees responsible for electricity planning and provisions in the country can, therefore, incorporate mini-grids into the national electrification master plans, primary electrification policies and strategies. Module 1 initially describes policies that can effectively encourage private-sector investment in mini-grids, as well as new and evolving technologies to spur private investment for remote electrification projects. For promoting large-scale investment in decentralized projects, streamlined licensing regulations by the nodal agencies are essential. The licenses can indicate the transparent legal procedures and establish options for microgrid owners if centralized grid extensions reach remote locations during the energy service tenure.

Decentralized electricity systems occupy a significant part of the energy ecosystem, but the central utilities often consider off-grid systems a competition to their established markets. The effective regulations for prioritizing centralized grid expansions over decentralized systems and discouraging tariff models are critical factors responsible for hindrance towards improving rural electrification scenario.

"While most countries have national electrification plans, many of these plans may not include off-grid energy developments."[5] When microgrids play an essential role in a country's national electrification master plan, private companies and donors are more likely to invest, communities are more likely to support projects, and utilities are more likely to prioritize off-grid energy development [166]. The following vital elements incorporated in Module 1 of the CF could support the statement enabling an increase in decentralized projects for remote communities:

- Renewable Purchase Obligations (RPOs)
- Renewable Energy Policies
- Rural Electrification Policies
- Plans for replacing Diesel gensets
- Tender and Licencing Procedures
- Tariff Regulations

[5] https://www.usaid.gov/energy/mini-grids

- Rural Electrification Grants and Subsidies (Please refer to Appendix I for a detailed discussion of these elements).

3.3.1.1 Assessments of the international technical standards[6]

The International technical standards serve as a benchmark for technological interventions and activities globally. In the context of rural electrification, the technical standard IEC/TS 62257 provides a professional parameter to different players (project developers, implementers, installers, and participants) involved in off-grid electrification for the setting up of hybrid renewable energy systems [167]. To this extent, the assessment of the standard IEC/TS 62257, during the development of the CF, indicated the absence of a methodology for typology identification and classification of the rural electrification systems. This incompetence in the technical standard IEC/TS has led to degradation in the value proposition of microgrids and deployments for end-use applications. The amendments in the technical standard indicated in the CF, therefore, hold a significant contribution towards scaling up deployments of off-grid remote microgrids.

The literature reviewed suggests academic research on developing the building typologies for urban scenarios, archetypes, and benchmark models. However, these typology identifications

[6] Part of this section has been published in: A. Chatterjee, D. Burmester, A. Brent, and R. Rayudu, "Defining a remote village typology to improve the technical standard for off-grid electrification system design," in 2018 Australasian Universities Power Engineering Conference (AUPEC), 2018, pp. 1–5.

cannot be replicated in the rural electrification scenario for developing countries [68]. Furthermore, the technical standards established for the rural electrification systems deliver a complex methodology for typology classification of the decentralized electrical systems. These complexities yield to the differences in the sizing and selection parameters for microgrid models, thereby, leading to the failure of the energy models to meet the desired load demands. Considerations in the technical standard that can aid in overcoming the challenges and pave the way towards an increased microgrid deployment include the following:

- A proper typology identification and classification of villages in developing countries; and
- Improving the technical specification standard IEC/TS 62257-2 (section 5.7.) for a rural electrification typology classification based on the corresponding energy dispatch strategy (discussed in Module 2 of CF)

The need for a distinctive identification of the village typology arises from the following aspects:

- A typology identification determines the scale and the type of energy system model required for a specific site based on the end-use applications.
- A microgrid project based on a distinctive typology results in a systematic data tracking of the performance of the plans for long-term operability, resulting in proper maintenance and growing

interest among the nodal agencies to invest for new microgrid ventures and projects.

- A typology identification can determine the future trade-offs for the project with aspects to load sharing and capacity extension.

The need for a discussion in the village typology identification in Module 1 arises due to its impact on the initial project preparation stages, where the typology assessment can aid in strategizing the proceeding/functions, activities, and duties of the stakeholder-energy provider for further development of the microgrid project.

A typology for urban electrification is generally a unanimous taxonomic physical characterization of the building, structures, and archetype, delivering a distinctive feature of the human development index, human settlement pattern, the end-use applications, and its intensity of development. However, an anomaly observed in generalizing the typology of rural electrification compared to an urban scenario, especially in developing countries. The defect is generally a consequence of the lack of a distinctive typology of the village classification and identification, resulting in an inadequate rural electrification typology. An inaccurate rural electrification typology results in inefficient techno-economic assessments of the microgrid developments at a selected site. An inefficient TEA poses a threat to the energy models designed to meet the end-use application resulting in the discrepancies of the microgrid deployment and the project failures leading to the lower acceptance of the microgrid models.

The classification of village typology is a crucial task in this entire process even though there is no unanimous agreement on a distinctive designation of a rural community. Some essential criteria can, however, be considered for a village classification for developing countries.

One such criterion involves classifying the village based on migratory patterns, namely migratory agricultural village, a semi-permanent agrarian village and a permanent agrarian village. A migratory agricultural and a semi-permanent agricultural community constitute the dwellers living in fixed abodes only for few months and migrate after that. A permanent agricultural village is an essential aspect for electrification considerations considering that the despondent inhabit the village for generations and contributes towards the overall socio-economic development of the community.

Another criterion for a village typology classification involves the village structural pattern, such as an isolated farmstead, a line village pattern (LVP), a circular village pattern (CVP), a market-centred settlement (MCS), and hamlets. To adequately describe the classification features, an isolated farmstead is often described as an individual settlement with farmland surrounding the residence. An individual electrification system (IES) is suitable for such a typology where the hierarchy for electricity access holds for the household electrification at the apex criteria, followed by energy access for some agricultural activity.

The LVP constitutes households of the dwellers near each other along with their farmlands in nearby accession, while a CVP consists of houses arranged in a circular enclosure within a central area. The MCS is inhabited by families and commercial activities such as banking, agricultural storage and trade centres, as well as public amenity centres. A combined electrification system (CES) can be considered suitable for LVP, CVP and MCS village typology where electricity access is required for both the houses and the commercial activities in the village.

A hamlet often referred to as the isolated and unidentified villages with topographic challenges, is the complex form of typology. The village site poses a challenge for uniform electricity access as the settlements can be in a distant location to the mainland area, as these hamlets can be islands surrounded by the seas; also, a delta region or settlements at extreme higher altitudes compared to the surrounding areas. A CES is a key to such a typology where the electricity loads comprise of an entire village model: household, agriculture, semi-commercial activities, health centres, schools, temples, social and public amenity centres, as well as the streetlights. Such villages are characterized by a close-knit social organization fostered by their residential proximity, contact, community sentiments and ideas, and are most dominant in the remote locations of the developing countries of sub-Sahara African nations and the Asian countries especially India, Bangladesh, Vietnam and Indonesia.

3.3.1.2 Energy target identifications and strategies

The Acceptance, Operation, Maintenance, and Replacements (AOMR) actions play a vital in defining the dimensions of the participation of the stakeholders and the responsibilities of the project developers over the entire lifespan of the project. Table 3.1 outlines the AOMR actions, where setting the AOMR actions acts as a bridge between the project developers and the stakeholders for a successful project functionality, while Table 3.2 tabulates the AOMR participatory indicators and the activities involved for the project.

Table 3.1: Acceptance, Operation, Maintenance, and Replacements (AOMR) Actions

Acceptance (A)	o Checking process to ensure system installation meets the requirement outlined in the implementation contract between project developer and implementer o A testing process providing project functionality according to the functional part of the implementation contract o Transfer of responsibilities as and when required
Operation (O)	o Managing the business of service o Monitoring regular system operation as per the guidelines and technical specifications o Response to abnormal system conditions and incorporating resiliency o Troubleshooting of the system, safety, and hazards o Analysis for capacity expansions and retrofits
Maintenance (M)	o Preventive maintenance: ensuring normalcy of the project o Corrective Maintenance: adjusting, fixing or replacing components after fault recognition o Conducting periodic tests and inspections
Replacements (R)	o Replacing equipment on typical life cycle completion o Replacing equipment for up-gradation purposes of the project o Dismantling and recycling of the equipment at the end of the life cycle of the project considering the sustainability aspects and adhering to standards.

Table 3.2: The AOMR participatory Indicators for Microgrid Projects

Nature of Participant	AOMR Actions				Responsibilities versus AOMR Actions
	A	O	M	R	
Owner	Ir			Ir	Long term financial and contractual responsibility of the system
Project Developer	Ir	Cr	Cr	Cr	Defining operating rules, maintenance policy and replacement schedule
Consultant	Ir			Cr	Defining the AOMR rules and the levels of services
Implementer	Ir				Information of relevance related to AOMR to the project developer
Sub-contractor	Ir		Ir	Ir	Warranty specifics for the project parameters and equipment
Operator		Ir	Ir	Ir	Project approval and ensuring project maintenance
Maintenance Contractor			Ir		Site visit for ensuring project status, maintenance and future capacity extension reports
Training Provider		Tr	Tr		Relevant knowledge and training to operators and users
User		Ir	Ir		Feedback and project participation. Understanding the rules and regulations
Where, Cr= Conceptual Role, Ir = Implementation Role, Tr= Training Role					

3.3.1.3 SWOT analysis for project assessment

The SWOT analysis for a microgrid project can be effectively used for business and marketing analysis. In general, the SWOT framework is composed of internal and external assessments [168]. The internal evaluation is conducted to illustrate the strengths and weaknesses of an organization or a strategic plan; the external assessment is applied to discover opportunities and threats. Strengths stand for any available resources that can be used to advance the performance. Weaknesses are flaws, which may decrease competitive advantages, efficiency or financial resources. Opportunities are external changes that could contribute to additional development, while threats are outside factors that may cause problems. In the energy management field, SWOT has typically been used to analyze energy situations of a single region or system. The SWOT analysis[7] can be done as part of strategic planning, or as a stand-alone activity, independent from other processes. By capitalizing on strengths and eliminating or correcting weaknesses, a project is better enabled to take advantage of opportunities as they emerge and cope with threats before they become a reality.

7 http://work911.com/planningmaster/faq/swot.htm

3.3.2 Module 2: Project Baseline Analysis

Typology of Rural Electrification
Dispatch Strategy for Rural Electrification
Load-demand Assesments and Capacity estimation
Electrical Appliances Identification and Usage Pattern
Surveys: {land avilability , occupation background of dwellers, commutation access, knowledge skill levels, per capita income and wages of dwellers}
Land ownerships, Human Resource Availability
Resource Assessments : {Weather, rainfall, temperature}

3.3.2.1 Typology of Rural Electrification[8]

The typology of rural electrification was classified based on the topology of the village identified in the previous module. The rural electrification scenario, as seen in Fig 3.4, is predominantly classified based on the purchasing power parity, qualitative electrification requirement, and the quantitative electrification requirement.

The purchasing power parity signifies the economic status of the despondent to purchase electricity for end-use applications. For developing countries like India, the poverty level, the class, and cultural segregation based on caste systems play a crucial role in determining the power purchasing capacity of an individual. The desired usage establishes the qualitative electrification requirement

[8] Part of this section has been published in: A. Chatterjee, D. Burmester, A. Brent, and R. Rayudu, "Defining a remote village typology to improve the technical standard for off-grid electrification system design," in 2018 Australasian Universities Power Engineering Conference (AUPEC), 2018, pp. 1–5.

concerning the type of appliances for used activities such as for household (lighting, cooling, and entertainment), public access (street lighting, schools, and health centres) and economic (commercial and agricultural appliances). Also, the factors comprising the duration of services (Wh/day), availability of services as well as, the power quality and reliability play a vital role. However, the quantitative requirement considers the number of appliances required for the application (domestic, semi-commercial, IoT, community-based, and deferrable loads) and the archetypes existing in the village.

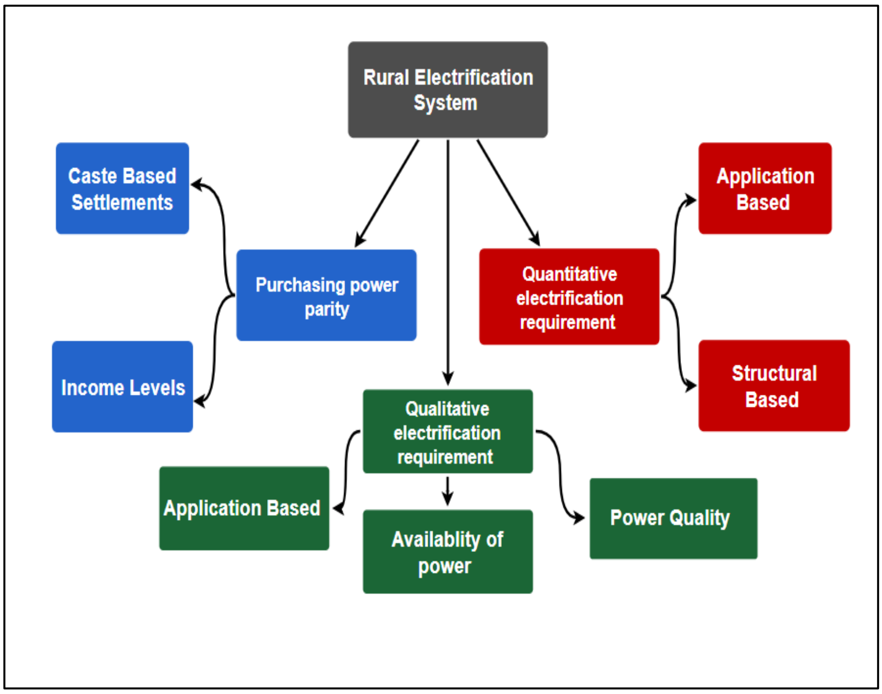


Fig 3.4: Typology of Rural Electrification System

The classification above is essential to model and design the microgrid system layout and the parametric selections for the energy production, distribution, and the application subsystem of the remote electrification architecture. The International Electrotechnical Commission (IEC) is a worldwide non-profit organization that develops and publishes consensus-based international standards

[167]. The IEC collaborates closely with the International Organization for Standardization (ISO) for standardizing and promoting world trade while encouraging economic growths [167], [169], [170]. The standards committee provides the requirements, specifications, guidelines, and characteristics of the electrical components that can be used consistently to ensure that materials, products, processes, and services are safe, efficient as well as, environmentally friendly. Also, the standards stimulate a dialogue between the national development organizations, the national Electrotechnical committees (IEC National Committees), and public policymakers. The IEC 62257-2 is used in conjunction with the IEC 62257 series comprising the "Recommendations for small renewable energy and hybrid systems for rural electrification" [167]. The technical specification (TS) has been prepared by the IEC TC 82: Solar photovoltaic energy systems with the text of the technical specification based on the document as inquiry draft: 82/302/DTS and report on voting: 82/320/RVC [167], [169].

The IEC/TS 62257-2 constitutes a generic TS for the renewable energy electrification ranges and the typologies and has negated the importance of the remote electrification of the developing countries, which is a critical issue for all the developing nations. Also, the TS has, since its inception, not emphasized the Millennium Development Goals (MDGs), and later the SDGs. As such, the electrification system source considered in the TS consist of the generator sets (gensets) in addition to renewable energy sources. The constant presence of the gensets as the source of energy over the years has led to hindrances in the usability and deployment of single/hybrid systems renewable energy-based systems for rural electrification [169]. The use of gensets has also led to complexities in the typology for a remote electrification production system, as shown in Table 3.3.

Table 3.3: Typology of remote electrification production subsystem archetypes

S.no	Energy Generation Source Type	Storage	System Classification	
			Individual	Collective
1	RE * only	✗	T_1 I	T_1 C
2	RE only	✓	T_2 I	T_2 C
3	RE + Gensets	✗	T_3 I	T_3 C
4	RE+ Gensets	✓	T_4 I	T_4 C
5	Gensets only	✗	T_5 I	T_5 C
6	Gensets only	✓	T_6 I	T_6 C

Notation:
*RE= Renewable Energy
T_i I = Individual Electrical System, T_j C= Collective Electrical System

3.3.2.2 Dispatch Strategy for Rural Electrification[9]

The classification further complicates the typology of the electrification based on a dispatchable system (DSP) or a non-dispatchable (NDSP) system. The TS specifies the renewable energy sources as the NDSP, where the NDSP is incompetent in generating

[9] Part of this section has been published in: A. Chatterjee, D. Burmester, A. Brent, and R. Rayudu, "Defining a remote village typology to improve the technical standard for off-grid electrification system design," in 2018 Australasian Universities Power Engineering Conference (AUPEC), 2018, pp. 1–5.

and providing uninterrupted electricity all the time. As such, the unreliability in electricity provision affects the deployment of the renewable energy-based systems, which leads to gensets as favourable choices for the electricity access to the remote communities. Fig 3.5 shows the categorization of the systems based on the dispatch criteria.

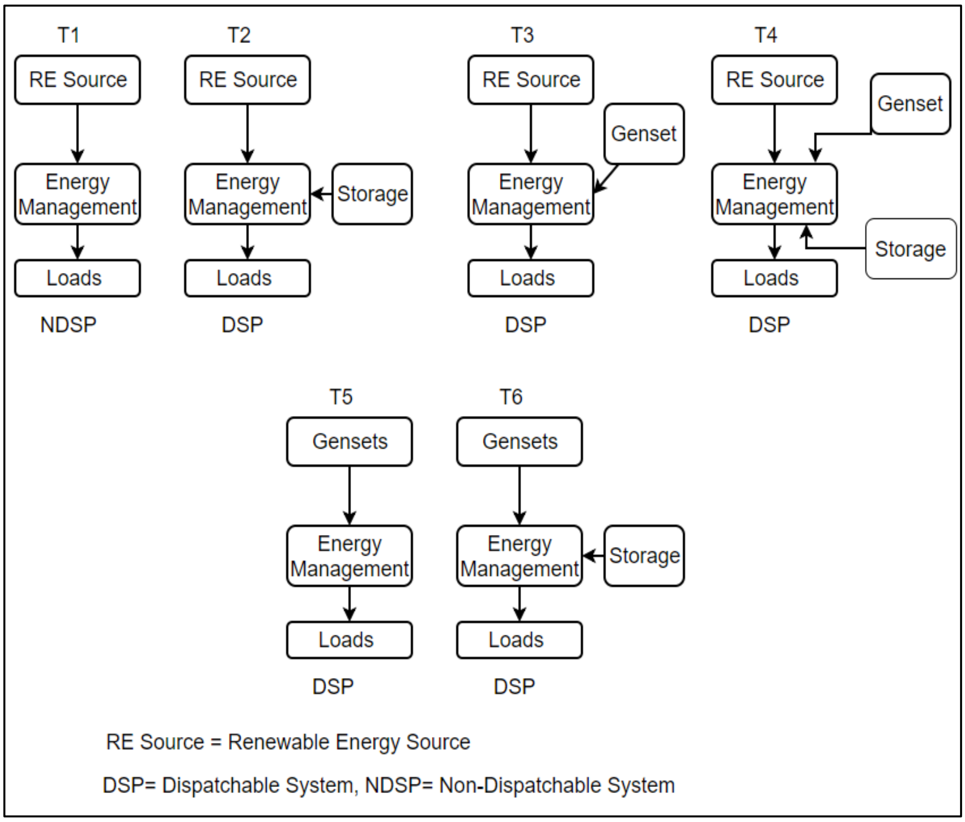


Fig 3.5: System Architecture and dispatchable strategy based on the typology of rural electrification

The existing TS in the standard IEC/TS 62257-2 needs to be amended to improve the value proposition of the decentralized systems for remote electrifications. Here, the changes to adapt to a sustainable approach of electrification are required where the emphasis should be given to the renewable energy sources over the gensets using kerosene and diesel as fuel sources. Also, the complexity in the system classification based on the dispatchable technology should be negated for rural electrification. The provisions for the inclusion of storage systems for all the electrical systems (single and hybrid renewable energy systems) should, instead, be made mandatory for a reliable and resilient systems approach. A storage system can, however, be neglected for deferrable load applications, which are carried over in a specified daytime. The reduction in the complexity can be addressed by referring to Table 3.4 below for remote electrification in a developing country. Proper identification of the village typology, along with an identification of the typology of the rural electrification scenario for a developing country, can be utilized to assess the microgrid system desired for electricity provision at an individual or community level. Thereafter, the amendments suggested in this article for the TS standard 62257-2 can be effectively used for the TEA in order to increase the value proposition of the microgrids.

Table 3.4: Improvisation to the typology of remote electrification production subsystem archetypes

S.no	Energy Generation Source Type	Storage	System Classification	
			Individual	Collective
1	RE (single source)	✓	T_1 I	T_1 C
2	RE (hybrid source)	✓	T_2 I	T_2 C

3.3.2.3 Demand Assessment

While providing electricity access to households is essential, planning electricity supply facilities only for homes is not desirable for overall economic development. Particularly in areas devoid of electricity supply, the demand for energy (and energy-using services) for meeting other associated amenities for everyday life must be assessed and met. A wide-ranging demand assessment would also help in ensuring economically efficient development of local energy resources about the timing of construction, the size and projected life of the energy facilities. Demand assessments that are comprehensive and multi-sectoral in coverage are, therefore, desirable methods of assessing the energy demand of the communities, which is an enabling factor in determining the additional energy requirement that must be provided during the energy access planning period to meet the acceptable minimum level of primary energy services. The choice of the appropriate method is subject to several factors, such as the nature and availability of the underlying data, the purpose of the analysis and the time frame. For many long-term planning exercises, demand projections are based on some econometric relationship to income (gross domestic product), energy price and population growth projections, along with an elasticity relationship. In the context of electrification, parameters such as household connections for demand projections play a pivotal role and should, therefore, be considered as a primary load focus.

Assessing energy service demand in the target area involves evaluating the energy demand of households for consumptive and productive uses of energy, as well as the energy demand of the community services. The energy service demand of the production sector is associated with energy use in activities such as the operation of machinery for agricultural production and agro-processing, water pumps, as well as tools for small and medium-scale manufacturing industries. The demand for energy in community services covers energy use for health care services (such as hospitals, clinics and health posts), education (such as schools, universities and other education services), public institutions (such as government offices, religious buildings), and infrastructure services (such as water supply and street lighting).

3.3.2.4 Resource Assessment

A detailed assessment and knowledge of available energy resources and their associated development are crucial objectives for ensuring an available and reliable energy system. The resource assessment in this framework focuses on primary energy resources. In the case of electricity access programs, these comprise local renewable energy resources in the geographic area where an off-grid system is developed. The resource assessment generates information about the economically exploitable potential of available energy resources, their spatial distribution and seasonal variation patterns over different periods in a year. The assessment also indicates the cost involved in harnessing the resources. Also, the resource assessment provides information about other important aspects of resources, e.g., their proximity to users, ease of access to the resources, as well as the adequacy of the resources given the current and future demand for energy. Some vital information from the resource assessment is used in the cost assessment of components or the sustainability assessment of resource and technology options under the framework. The various dimensions of resource assessment and the approaches to resource assessment undertaken in this study were based on [171]:

- Availability of Resources: The availability of a resource in the context of resource assessment refers to the economically exploitable potential of resources, including decentralized or local energy resource options, and the spatial and temporal distribution patterns of the resources.

- Adequacy of Resources: The resource assessment determines whether enough resources are available to meet the energy demand in the energy access planning area over the short, medium, and long term. A resource that is consistently available in sufficient quantities to meet local demand over a longer-term should be preferred to a resource that is insufficient to meet either the present or the projected demand or is only intermittently available.

- Sustainability of Resources: In general, success in supplying a community with its energy needs depends on the sustainability of the resources. The resource assessment, therefore, also considers whether one resource is more sustainable than others from an environmental, health, energy security and economic standpoint.

- Ease of Access to Resources: Another aspect covered by the resource assessment is the ease of access to a resource for its economic exploitation; for example, how far one must go and how many hours one must spend to collect the fuel.

- Cost of Resource Use: The resource assessment must determine the value of using a resource to provide access to essential energy services. The costs associated with a resource can vary with the amount used. Information about the value of resources would help in determining the most cost-effective resource.

The spatial distribution of energy resources mapped over different periods is the primary basis for the resource assessment. Maps of renewable resources (biomass, hydropower, solar, wind) are often available in relevant national databases or international sources. Many countries already have such information and may have used it as part of national energy (including electricity) planning. Countries without a comparable database will have to collect data to assess energy resource availability, particularly about their economic potential in the project target area, but primary data collection can be both costly and time-consuming. As far as possible, therefore, information about local energy resource potential can be compiled from the available GIS database and other secondary sources.

3.3.3 Module 2a: Retrospective Cohort Analysis (RCA)

Existing Rural Microgrid Assessments
for
Regaining Status for Stalled Microgrids

A retrospective study looks backwards and examines exposures to suspected risk or protection factors about an outcome that is established at the start of the study. In a retrospective study, in contrast to a prospective study, the issue of interest has already occurred at the time the study initiated. There are two types of retrospective research, namely a case-control study and a retrospective cohort study. A retrospective study design allows the investigator to formulate hypotheses about possible associations between an outcome and an exposure while investigating the potential relationships further.

In the CF, RCA has been implemented to analyse existing microgrids in rural communities. The use of RCA would help in determining the functional status of the existing microgrids, as seen in the previous chapter, where underpinning microgrids were identified based on CAARLS attributes. The use of RCA would enable the failed microgrids to regain normalcy, thereby spurring the microgrid projects, in addition to the new microgrid project establishments.

3.3.4 Module 3: Prospective Analysis

Rural Microgrid Assessment and Regulations
Indicators towards Project Sustaianability
Parametric Selections
Electrification System Designing and Architecture
Electricity Source Configuration
Electrification system sizing and source optimization
Energy Management Techiques
Energy Efficiency Approach and Assesments
System Resiliency/Autonomy
Socio-Economic Regulations and Assessments

Module 3 of the CF, as shown in Fig 3.6, details the techno-economic assessment required for the establishments of microgrid projects. Microgrids are composed of energy production systems, energy distribution systems and end-user systems. Off-grid microgrid technical design is the process of selecting the components and configurations for each system that will deliver reliable, cost-effective energy services that meet the needs of end-users.

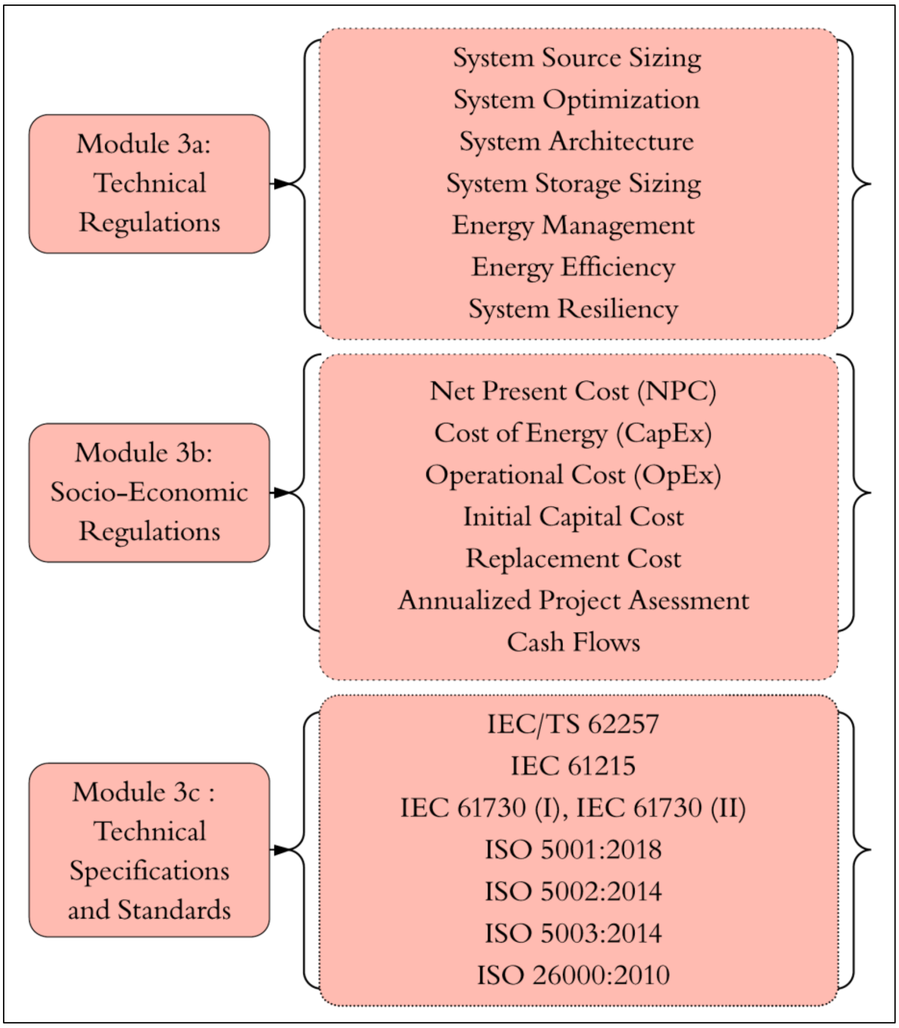


Fig 3.6: Further fragmenting Module 4 of the techno-economic analysis

The essential technical components of a microgrid are grouped into three systems, namely:

- Production System
- Distribution System
- User Supply

Considering the aspect of sustainability, which in the present context of the research ignores the use/purchase of the fossil fuels, and complete reliance on using renewable energies as the prime source of energy supply for the microgrid system, it is of vital importance to understand the functional description of the energy management system for the rural microgrids. Since the availability of the resources varies considerably, energy management is a crucial task in the provision of electricity services promised at the energy supply end in the best possible condition without jeopardizing the operating life of the system parameters. Fig 3.7 below illustrates the energy management role and the component functionality in a microgrid system.

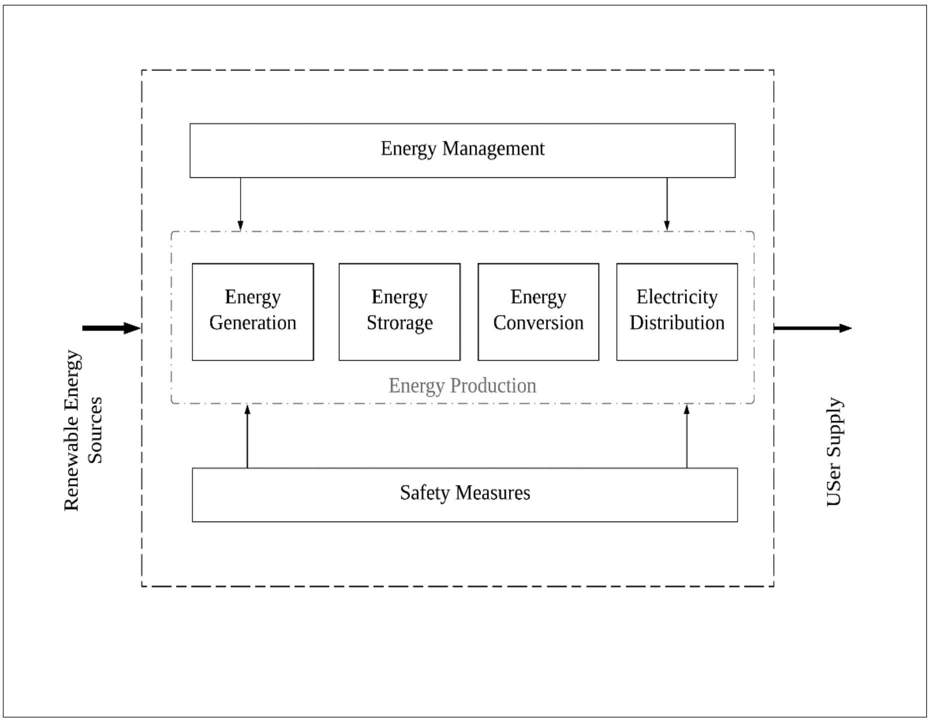


Fig 3.7: Functional Impact of an energy management system

To effectively manage energy in REN systems, several functions need to be considered, as described below:

- Adequate management of resources and needs: To efficiently manage energy in an isolated system, consideration shall be given to the overall production from renewable energy sources and energy consumption, ensuring that the resources match the demand for energy, then taking the appropriate action. This management must comply, as strictly as possible, with the commitments of the entity providing the services (the project developer and operator). This task should, therefore, be completed in the best interest of the user perspective.

- Giving precedence to the use of renewable energies: Energy management in an isolated system is to give priority to generation from renewable energies in order to reduce consumption of fossil energy and lower system operating costs.

- Maximizing service life and performance of equipment: Managing energy in an isolated system also involves ensuring a long service life for the equipment. Here, the management strategy entails giving precedence to equipment protection so that the capital investment is used correctly throughout the service life for which the equipment has been designed.

- Managing the storage system: Quality of battery management has a very high impact on battery life, on the system's level of performance and life cycle cost.

- Managing the available quantity of energy: The task involves maximizing the use of the available REN, which is generally limited and optimizing the sharing of the available amount of electrical energy produced from the REN, amongst the different users or appliances. The excess energy patterns generated during the system operations should be minimized by considering energy-efficient systems and system design approaches.

The autonomy of the system, though neglected in the literature, considered in the CF, has been shown to have a substantial impact on the overall reliability aspect of the microgrid system. A microgrid, without system autonomy, would still be able to balance the load requirement for standard operating conditions, but inadequacies arise in events of a power outage due to a fault in the power system components or natural catastrophes. The specified system protocol for autonomy is typically between 2 and 12 days [132]. However, a 3 day autonomy has been considered in this research considering the factors of power insurgency due to technical or system faults, but not natural disasters or catastrophes [17], [67], [86-88], [101-103], [127], [132]. A system designed using more days of autonomy will have higher reliability than one with fewer. Nevertheless, increasing the autonomy increases the required battery bank capacity and increasing system cost, however, the reliability does not necessarily proportionately scale with the days of autonomy. A resilient approach towards microgrid design that accounts for irregularities be a fundamental task for an uninterrupted power generation to the end-use application. As such, an effort to refine the existing definition of a microgrid, with an emphasis on a resilient approach, is an essential step towards revising the value proposition of microgrid.

A system dynamics approach needs consideration where the generation of power, with the use of renewable energy for the electrification, can vary due to the intermittency and variation in the sources. The effect of changes in the energy ladder also plays a vital role in the overall system performance over the project lifetime. A sensitivity analysis of the microgrid system should be performed to analyse the impact of the variations arising in the system to maximize the system's lifetime. The differences can be in the form of cost inflation, load growth, system degradations 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.

In order to adequately define the size of the microgrid system, a proper system sizing is recommended. A systematic microgrid system sizing as shown in Fig 3.8 below, adapted and further revised in accordance to the current research from the IEC/TS 62257-4, ensures the reduction of excess energy generation in the system, in addition to reducing the overall cost of the system, which affects the establishments of the electrification systems in remote locations.

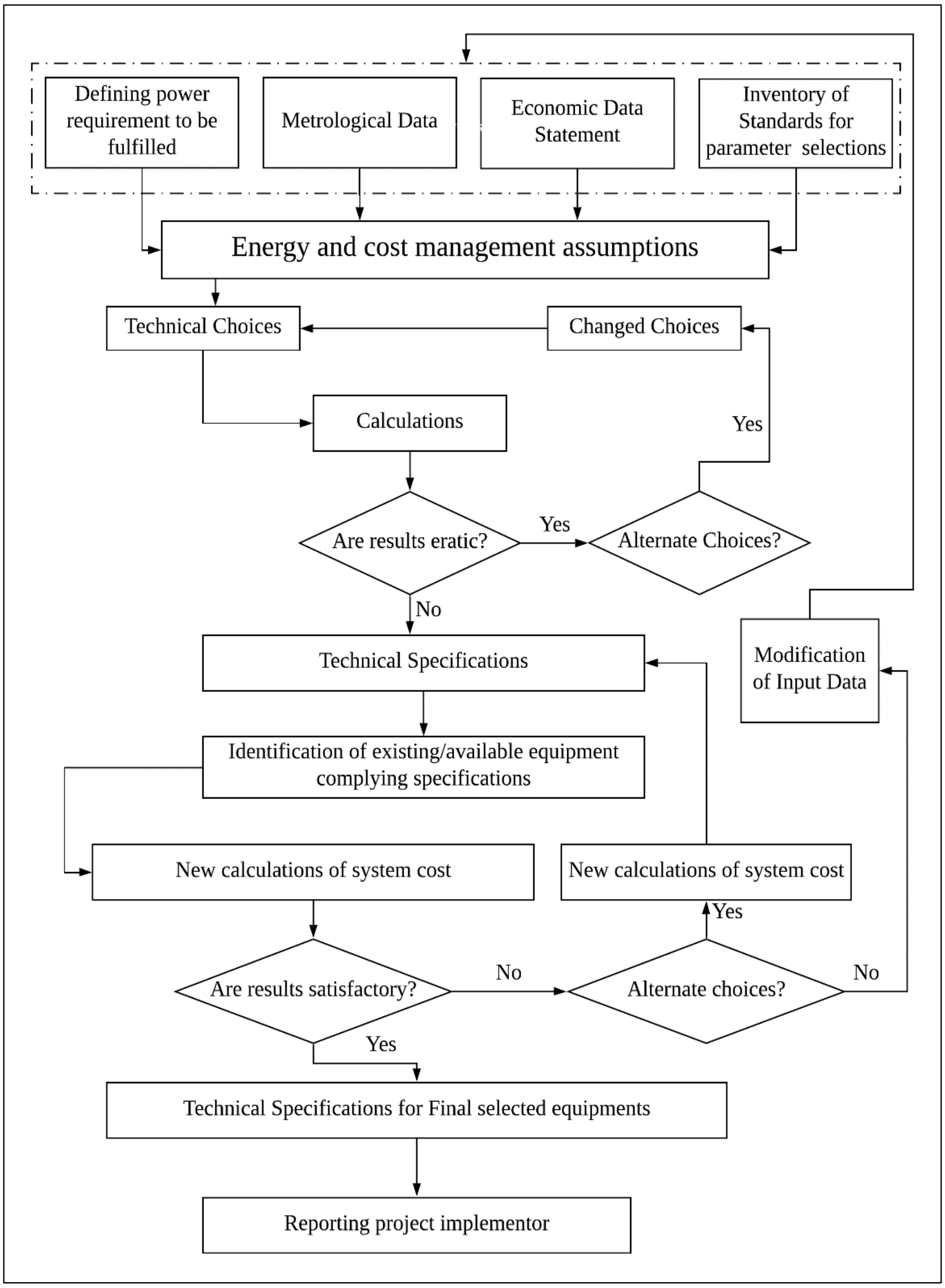


Fig 3.8: Sizing Process Flowchart (Adapted from [14] and further revised in the current thesis)

The cost assessment of microgrid projects is another essential factor that needs vital consideration. Financing mini-grids in developing countries is challenging. Mini-grid projects typically require long-term funding with a low cost of capital. Banks and nodal agencies in the developing countries are often reluctant or unable to offer long-term loans, either because they lack funds or cannot risk losses due to high or uncertain inflation. Also, microgrid project developers often lack experience in financial analysis, risk mitigation, as well as business plan development, and may not have resources to hire dedicated financial professionals. Securing loans is more complicated if the project developer cannot meet equity requirements considering that project investors require higher financial returns to compensate for the risk of mini-grid projects developed in risky political and economic environments. As such, knowledge of cost calculation for the off-grid microgrid projects needs attention.

In the context of the sustainable microgrid off-grid systems, the overall objective of the cost assessment is to determine the cost-effective options for providing access to cleaner energy sources, the total energy access cost (which includes both energy supply- and demand-side costs). The assessment would provide information about the total investment needed as well as other expenses, which are essential for microgrid project development and implementation. It also includes information about the per-unit cost of cleaner energy and the total cost of energy service to a poor household, which can be used to assess the energy burden implication (affordability) of an electricity system for communities. Such an assessment would have the following specific objectives:

- To estimate the incremental cost of providing different levels of access to electricity,

- To estimate the additional cost of giving access to varying degrees of cleaner nonelectric energy mainly for end-use applications like cooking and space heating, and
- To assess the incremental cost of expanding an energy or electricity access program in a country or within a subnational region.

Ideally, an integrated energy system model is used to determine the total cost of providing electricity services. The model tries to minimize the total supply- and demand-side cost of delivering energy access. The overall supply-side price includes investments in electricity generation technologies, transmission and distribution lines, as well as fuel, along with the O&M cost of supply-side technologies and resources. The investment cost associated with the local distribution system would depend on several factors, such as distance from the production unit, power demand, substation characteristics (including capacity, protection devices, transformer connection, etc.), population density and the gap between households.

The total demand-side cost includes an upfront cost (cost of devices and initial connection cost) as well as the O&M cost of demand-side devices. The model would minimize the total cost, provided that several conditions (or constraints) are met. A significant obstacle is the satisfaction of peak and off-peak power demand in meeting energy service demand (generally expressed as useful energy). Other limitations are related to limiting energy resource use for electricity generation (given seasonal or daily variations in resource availability) and not using any power generation unit beyond its installed capacity. The model may also consider the reliability of the electricity supply.

Fig 3.9 below presents an integrated methodological framework for assessing the cost of providing electricity access. The built-in cost assessment framework requires an electricity demand profile for different periods of the year, daily and seasonal variations in resource availability, as well as supply and demand-side technology options. The framework also requires data on the investment, fuel, and O&M costs of technology options on the supply side, as well as the upfront and O&M costs of devices on the demand-side. The framework stipulates the use of an electricity cost assessment model to determine the most cost-effective combination of supply- and demand-side options to provide energy services. Energy requirements for different service demands would be determined depending on the types of demand-side technologies considered. For each set of predefined demand-side technologies, there would be various combinations of supply-side technologies with differing capacities to minimize the corresponding supply-side costs. The cost assessment model has the following output: total electricity access costs (including energy resource cost, supply-side investment costs, and up-front demand-side costs), electricity generation and capacity mix (by type of technology and energy resource).

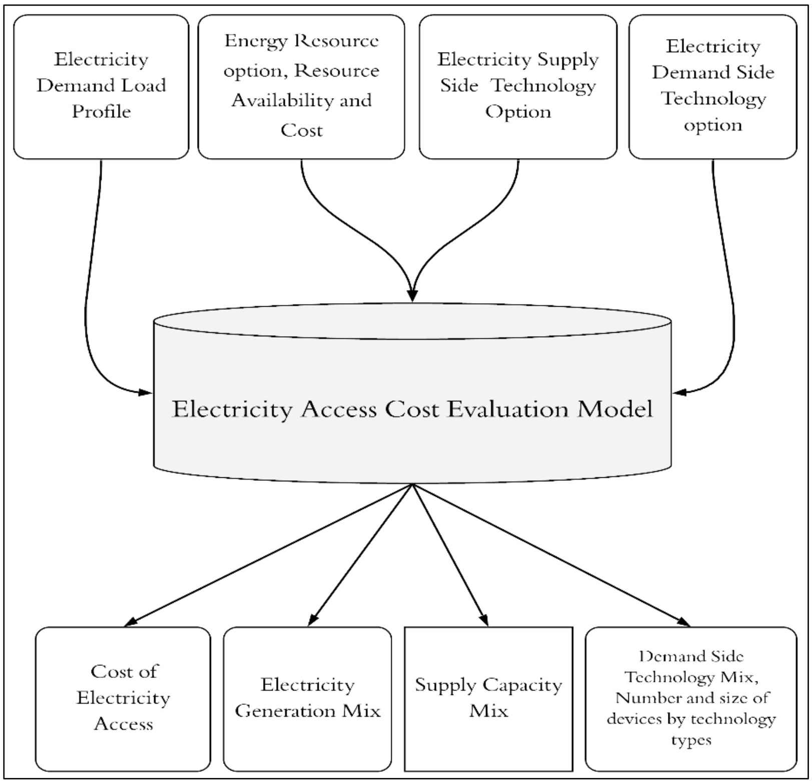


Fig 3.9: Strategic Assessment of Electricity Access Cost

3.3.5 Module 4: Implementation and Monitoring Analysis

Socio-Environmental Impacts,Indicators and Community Participation, Project Monitoring, evaluation and Appraisals,Project Report and Documentation, Post-Lifetime Project Disposal, Emerging Technology Identification

The last module constitutes the implementation and monitoring strategies. In this phase, the project monitoring, following the AOMR actions, needs to be considered. Generally, it has been observed that this phase of the microgrid project is often overlooked, thereby leading to system failures. This phase of the project is essential in preparing audit reports for the microgrid project. Regular monitoring of the system ensures a healthy working condition for the microgrid, providing opportunities for capacity expansion, and has a cost-benefit factor associated with it in terms of salvage value earned at the end of the project lifetime of 20-25 years for the remote microgrids.

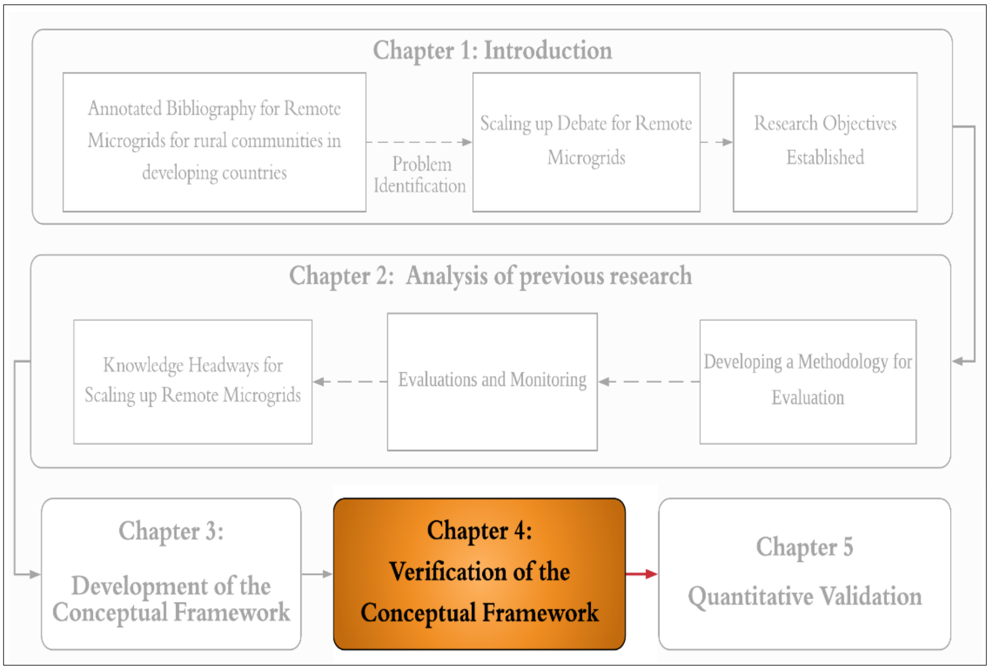
3.4 Chapter Summary

This chapter introduces a CF for the design of remote microgrids. The CF, framed by the SDGs, considers several closely linked factors: resources, cost, benefit, sustainability, and affordability, in order to plan out the ideal solution for an energy access program of high quality, broad reach and positive effects.

The following chapter delves into the verification of the framework, engaging a focus group of similar interests in sustainable energy developments for rural communities. The chapter also outlines the process flow of the modules developed in the CF post the various phases of the verification process.

Chapter 4

Verification of the Conceptual Framework



Qualitative research efforts use verification strategies to check the accuracy of one or more aspects of the research procedures, objectives, or contributions [172]. Features, such as research transparency, research flexibility to decisions and outcomes for improvements, as well as trustworthiness in the reporting of findings potentially lead to the credibility of the research. Transparency in research refers to clarity in describing the research process involving a thorough description of the steps/iterative processes undertaken in conducting the research. Flexibility in the research verification process enables revisiting the assessments or findings. Within qualitative research, the verification process incorporates two primary approaches [173], namely interviews or surveys, and focus groups.

There are potentially several different outcomes resulting from the verification process that is to do with the varied interests of the participants. However, "a researcher needs to be clear how this strategy was used and how the credibility of the research finding can be defined as the methodological procedures, thereby establishing a high level of harmony between the research objectives, participant's expressions and the interpretation of the researcher"[173].

Given the above consideration, a focus group approach was deemed appropriate for verifying the conceptual framework (CF). The selection is based on the criterion that "if the area of study is multidimensional with polarised views, regarding the differing interpretation of the world, words and their meaning, then focus groups may be appropriate"[172].

4.1 Selection of the Focus Group

The focus group selected for the verification process was the Working Group (WG) of the Institute of Electrical and Electronics Engineers (IEEE), Sustainable Energy Systems for Developing Communities (SESDC)[10]. The decision for selecting the focus group was based on the objective of the WG, which aligns with the goals of

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[10] http://sites.ieee.org/pes-sesdc/

"SE4ALL",[11] and other similar initiatives to achieve universal access to sustainable energy sources for the world's unserved communities. The WG is a multidisciplinary and global network of IEEE members with relevant expertise, diverse backgrounds and experiences. The WG exists to provide input to national and multinational decision-makers, practitioners, researchers and communities concerning issues about renewable and sustainable energy technologies, climate change mitigations and activities involving a low carbon society. The WG forum also allows for the following general contributions:

- Stimulate a Community of Experts: The WG seeks to be relevant to the pressing needs of developing communities, inclusive of differing perspectives and experiences, as well as awareness of the legacy of research already completed and new critical topical areas. The activities of the WG also aid in manifesting knowledge developed during the research activities by organizing panel sessions that adhere to the IEEE Power and Engineering Society (PES) guidelines[12,] which further stimulates interest in the scientific community for sustainable energy infrastructure.

- Raise Awareness: The WG seeks to raise the awareness of the engineering community on critical issues, learning and best practices for sustainable energy development, with a focus on sharing experiences, causes and solutions.

[11] https://www.seforall.org/

[12] https://www.ieee-pes.org/component/content/article?id=47:pes-authors-kit

- Provide Recommendations and Disseminate Knowledge: Establishing effective channels for the dissemination of knowledge is an equally important factor in achieving research impact as conducting and synthesizing research. Where appropriate, recommendations and position papers are the prime focus of the WG to manifest the knowledge among potential stakeholder groups, for example, to users, communities, practitioners, entrepreneurs and decision-makers.

- Organization of Research Initiatives: With the identification of the critical research needs within the remit of the WG, collaborative research initiatives, methodology guidance and organization of WG resources are encouraged. The activities are carried out by actively networking with sustainable energy initiatives, identifying member expertise areas and coordinating opportunities with WG members.

Also, the areas of interest that are identified by the SESDC form the basis for establishing tasks within the WG, namely:

- Task 1: Identification and description of the various dimensions of sustainability of electricity services for rural and remote areas in the developing world.

- Task 2: Critical review of world-wide Rural Electrification (RE) experiences, with reference to the impact of power sector reform and resulting institutional arrangements on the sustainability of electricity services in developing countries.

The WG aims to address the various dimensions of sustainability aspects and concerns regarding the provision of energy services to rural and remote areas. As such, it synthesizes knowledge and experiences while providing recommendations to decision-makers and user-groups to improve energy access in remote communities.

4.2 Phases of the Verification Process

The verification process comprised of four phases. The final phase comprised a collective closed-room discussion focussing on the research findings from the previous phases. Fig 4.1 below illustrates the timeline of the research verification process with each phase modifying the framework, based on constructive feedback from the panel experts.

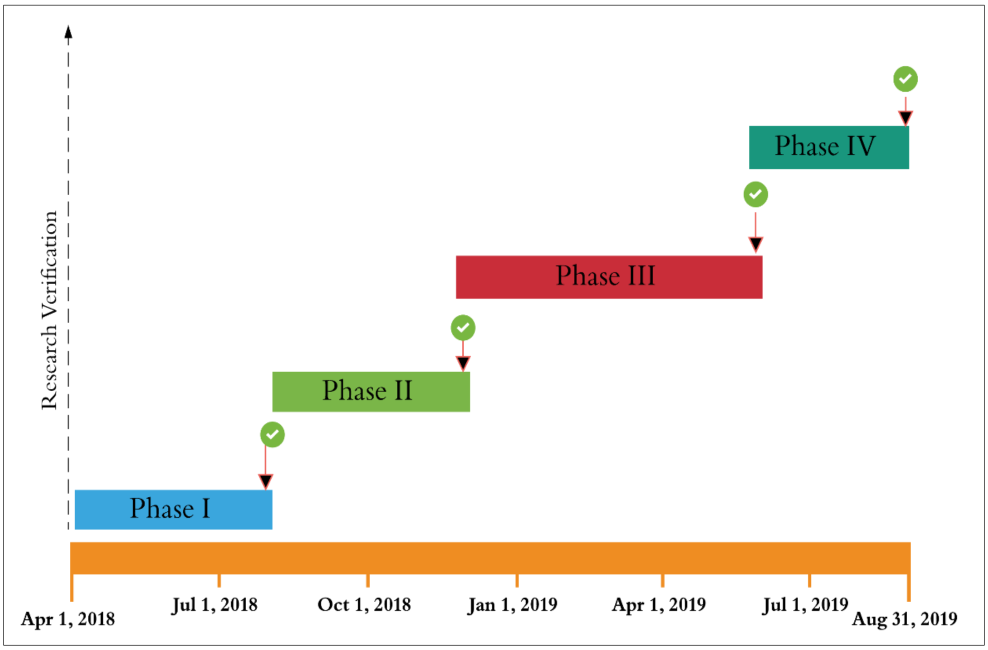


Fig 4.1: Timeline of the research verification

The verification process involved monthly virtual meetings, documentation circulated via emails with the SESDC taskforce during the entire timeline of the verification from April 1st 2018 to August 31st 2019. The meetings were facilitated by sending through documents and research findings to the SESDC taskforce, which were then discussed in the WG monthly meetings in ways of presentations and slide sharing. Also, the research findings were discussed for further diligence with the SESDC taskforce at the WG annual general meeting, where the CF was presented during an organized panel session at the IEEE PES General Meeting (PESGM) in Atlanta, the USA in August 2019. The meeting takeaways led to further research assessments and amendments for improving the CF. The details of meeting, transcription and notes summarizing the overlaps of the participants are detailed in Appendix II which indicates the meeting notes, the document sharing over emails, and the presentations constituting the CF verification loop process. The focus group comprised of experts from varied backgrounds, including academics, sustainability consultants, renewable energy practitioners from developing countries, industry experts in renewable energy developments and chairs from other sustainable development WGs as shown in Table 4.1. The verification process followed the ethical consideration of the university as there was no direct human or animal research involvements or surveys, neither the research nor any part of the verification involved human interaction for health, society or medical research. The experience levels of the expert participants are summarized in Table 4.1.

Table 4.1: The detail of experts during the CF verification

Category of experts and number of participants	Average experience of participants (years)
Academics (40)	15-20
Sustainability Consultants (10)	5-12
Renewable Energy Practitioners (30)	10-15
Industrial Experts (20)	3-10
Chairs of different IEEE WGs (5)	10-15

As indicated in the verification process and engagements with the WG initiated in April 2018, Phases I and II focused on the project preparatory analysis and the baseline analysis (Module 1 and Module 2) of the CF, and ways towards improving the components of the CF. Phase III reviewed the previous phases' results and emphasized on improving the TEA of off-grid decentralized systems (Module 4). Phase IV ended in August 2019, and confirmed the research findings, while paving the way for future directions and requirements to mobilize microgrid projects in developing countries.

4.2.1 Verification Phase I:

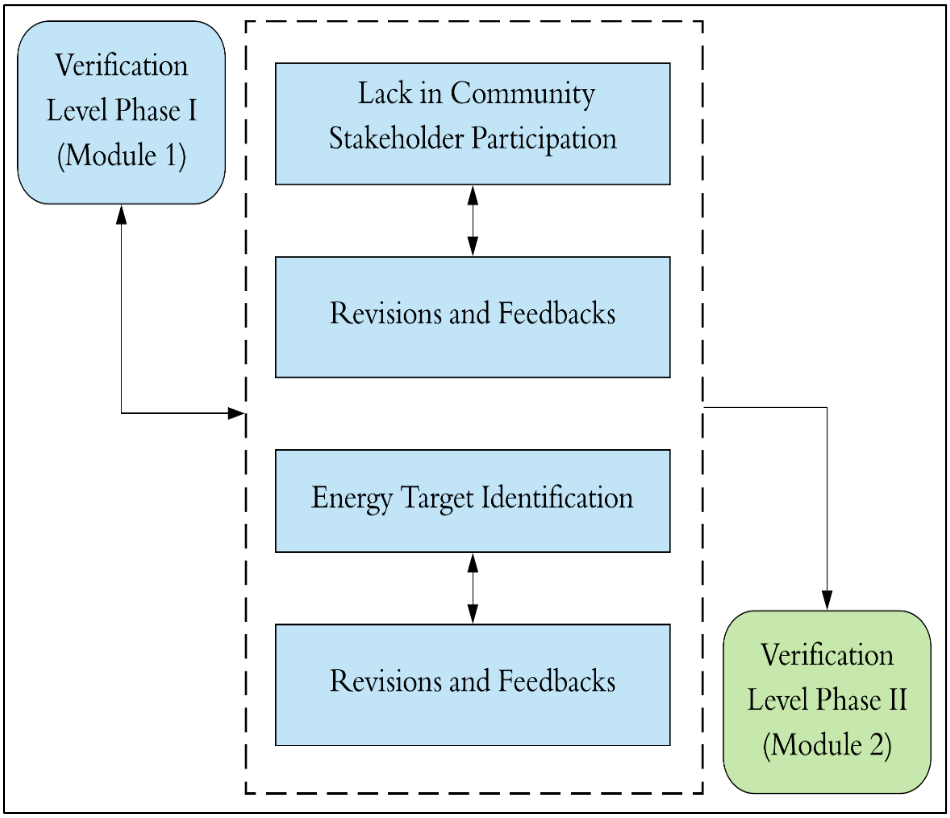


Fig 4.2 The strategy underlying the Research Verification Phase I

The taskforce involved in Phase I of the verification process, as shown in Fig 4.2, was the "Energy Use in Off-grid Applications" under the IEEE-SESDC. The expert members of the taskforce recognized the continued failure of many decentralized systems for remote/island, as indicated in Chapter 2, and attributed these failures to a single primary factor: "**lack in community stakeholder participation.**" This includes a lack of proper business models comprising negation of the participants from the community, lack of expertise in training and operation of the microgrids, asset management strategies, and holistic utility engagements.

The other aspects of concern were the national planning and policy assessments and the shortfalls in national rural policy and tariff regulations. However, the question regarding "**Community Stakeholder Participation**" generated the most significant degree of consensus in the WG, indicating a firm agreement on the importance of improving this aspect of Module 1 of the CF.

The issues identified by the experts further demanded a need for "**Energy Target Identifications**," since rural microgrid projects are site-specific with diversity in need for energy requirements.

4.2.1.1 Actions towards improvements from Phase I:

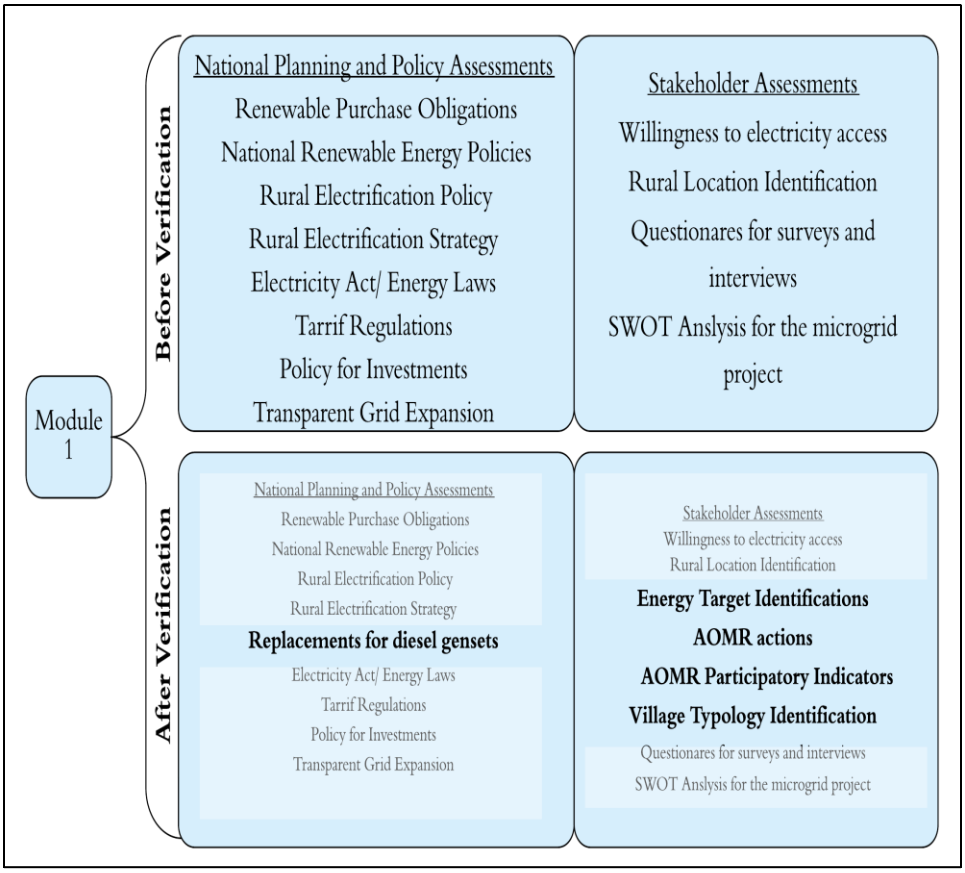


Fig 4.3: Comparison of Improvements (in bold) in Module 1, after the verification process

To encourage stakeholder participation in the remote, decentralized electrification projects, Fig 4.3 shows two crucial aspects considered as part of Module 1 of the project preparatory analysis for rural microgrids:

- o Identification of decisions for Acceptance, Operation, Maintenance, and Replacement (AOMR) actions (Table 3.1)
- o AOMR participatory indicators (Table 3.2)

The significance of these aspects introduced into the CF is an essential approach towards project initiation. Also, it is a critical task contributing to engaging the community in the project development processes and training the community for practical energy system usage. The steps introduced are an essential task towards improving the socio-economic aspects associated with microgrid projects. The socio-economic aspects are in accordance with an objective targeting the following sustainable development goals in the community:

- o Decent Work and Economic Growth (SDG 8)
- o Industry, Innovation and Infrastructure (SDG 9)
- o Sustainable Cities and Communities (SDG 11)
- o Responsible Consumption and Production (SDG 12)
- o Climate Change (SDG 13)

Also, the AOMR actions and the participatory indicators are essential towards establishing confidence among the project developers and the community for acceptance of the project, functioning of the project, and transfer of responsibilities, thereby enabling a redundant project/business development program.

Further improvements based on the discussions confirm establishing solutions for "Energy Target Identifications" where "Village Typology Identification" was introduced into the CF (see section 3.1). The inclusion of the segregating the villages in the village typology further contributes towards:

- Determining the scale and the type of an energy system model required for a specific site based on the end-use applications.
- The distinctive typology results in a systematic data tracking of the performance of the projects for long-term operability, resulting in proper maintenance and growing interest among the nodal agencies to invest for new microgrid ventures and projects.
- Future trade-offs for the project with aspects to load sharing and capacity extension.

4.2.2 Verification Phase II:

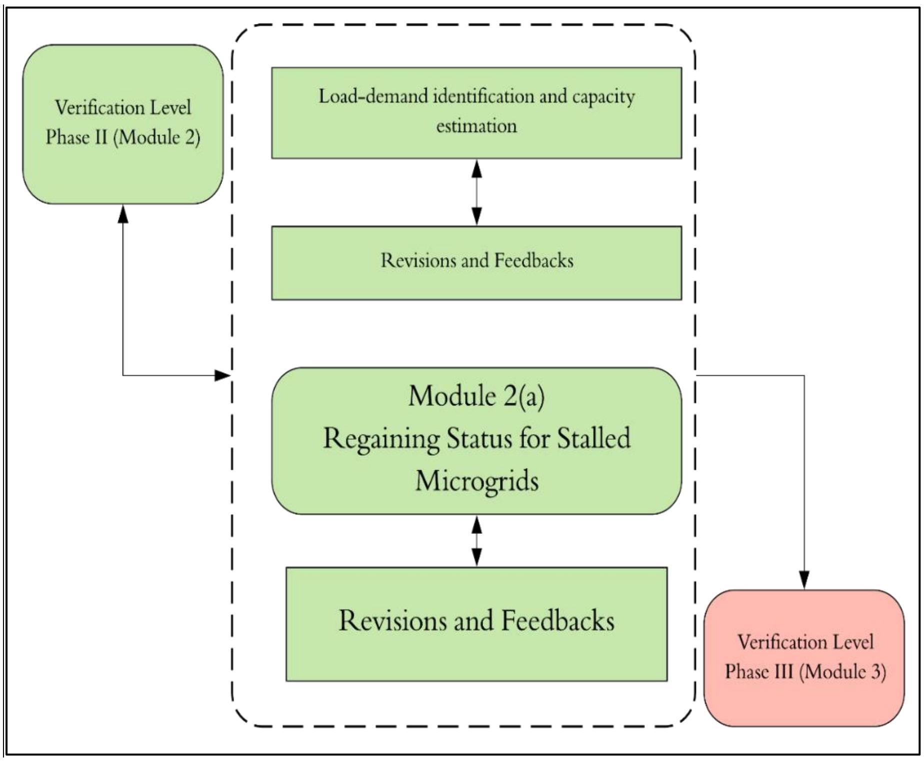


Fig 4.4: The strategy underlying the Research Verification Phase II

The feedback and the amendments incorporated into Module 1 of the CF paved the way for verifying Module 2 and introducing Module 2a into the framework, as shown in Fig 4.4. The taskforce committee involved in this phase of the verification process was the "Energy Use in Off-grid Applications" under the IEEE SESDC. The accomplishment in identifying the energy targets and establishing a rural typology led to the focus of Phase II. The essential aspects considered for the discussion was a feature to ensure proper "**Load-demand identification and capacity estimation**." The subsidiary discussions to safeguard the interest of the community for reliable energy access without compromising the climate change issues gained importance in this phase. Also, questions of ways to ensure and achieve prolonged and mandatory usage of renewable energy systems for electrification provisions were raised. Further, inquiries were made by the committee in accordance with "**Ensuring stalled microgrids regain normalcy.**"

4.2.2.1 Actions towards improvements from Phase II:

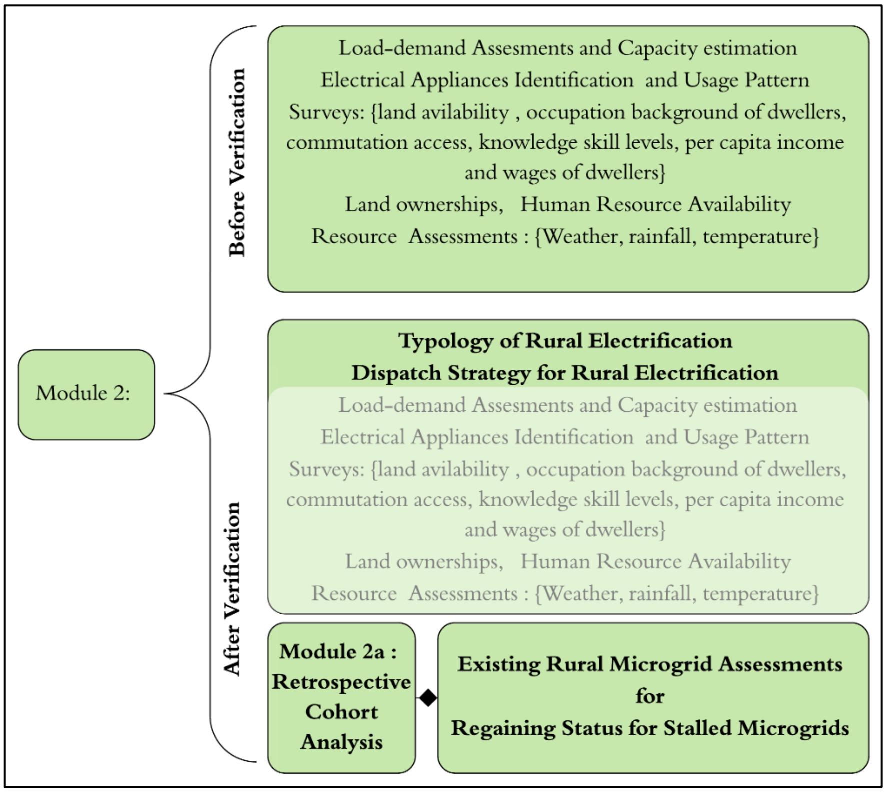


Fig 4.5: Comparison of Improvements (in bold) in Module 2, after the verification process

Fig 4.5 shows that the following measures were undertaken for the actions towards improving Phase II of the verification process:

- A rural electrification typology was defined.

- Amendments to the international standard were suggested by identifying production sub-system archetypes and a dispatch strategy based on purely renewable energy-based systems

The amendment for identifying an electrification typology for the rural perspective was considered to improve the design approach for off-grid systems. The typology identified, based on experiences of the expert in the committee, is valid for practical implications in the context of the remote communities in Asia and Africa. However, further comments from the experts suggested similar approaches can be effectively utilized for island communities with minor changes as and when required.

Moreover, the amendments to the technical standard gained the utmost attention of the WG committee. Considering the climate change mitigations and the action towards a low carbon society, replacing diesel gensets with a cleaner source of energy generation gained emphasis during the verification phase. Also, an important aspect indicated by the committee was ensuring a prolonged and mandatory use of clean energy sources as fuel. This resulted in revising the technical standards for microgrid designers, developers and energy practitioners. Phase II involved discussions that led to a deeper understanding of the implications of the amendments in the IEC/TS 62257 standard for energy dispatchable strategies.

Another critical aspect of regaining the normalcy for stalled remote microgrids was discussed in Phase II of the verification stage. The concern raised in this regard was resolved with the inclusion of a retrospective cohort analysis as Module 2(a) in the CF. The addition of

Module 2(a) yields to further diagnostics of the stalled microgrids, which can be performed by incorporating Module 1 and Module 2 of the CF leading towards Module 3 for re-establishing electricity generation services for the rural communities.

4.2.3 Verification Phase III:

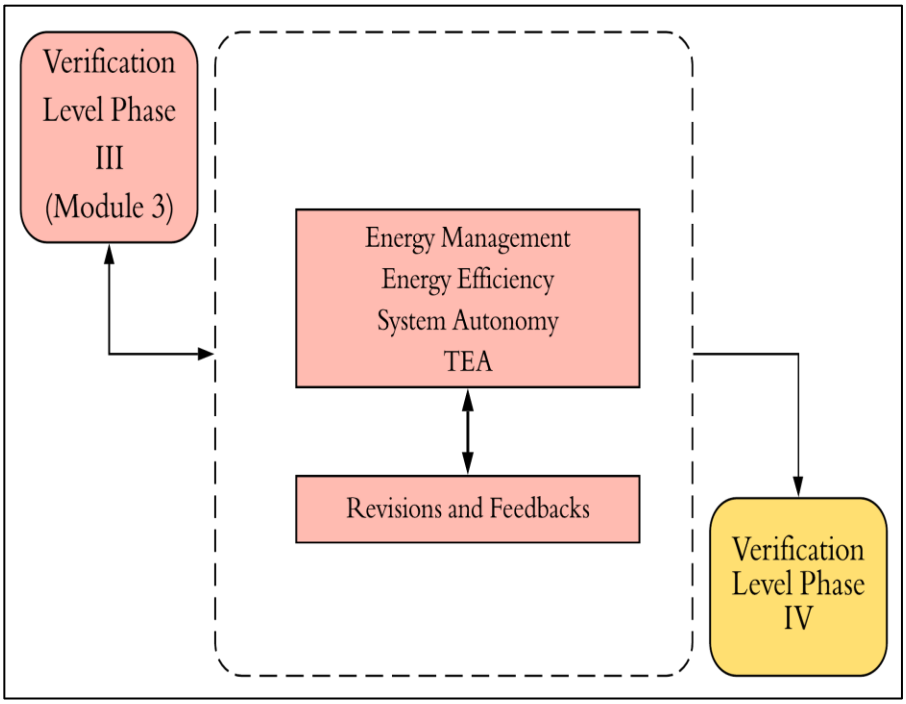


Fig 4.6: The strategy underlying the Research Verification Phase III

The focus of Phase III was on the TEA of remote microgrids. The verification during this phase involved the taskforce committee from the "Microgrids Pre-feasibility toolkit" under the IEEE SESDC. The underlying objective of the task force is developing a set of tools for determining the pre-feasibility of a microgrid in the context of developing communities. The inclination of the vision of the committee towards TEA and findings served as an appropriate audience for discussions, research improvements, verifications and further improvements in Phase IV, as seen in Fig 4.6.

The essential components of the discussion in Phase III involved the necessary technical measures for economically affordable systems to support/encourage microgrid investments. An emphasis was placed on improving the approach towards the TEA for remote electrification, where the issues of concern raised by the experts revolved around:

- Ways towards improving the energy efficiency of the system
- Ensuring clean energy provisions at a higher tier level of the multi-tier energy access level
- Ensuring techno-economic solutions to overcome the shortfalls in the governmental policy for rural electrification
- Uniform electrification
- How effectively energy can be managed to ensure efficient and maximum utilization of the energy sources installed.

Here, the most striking issue was the concern towards effectively enhancing the system autonomy in case of natural disasters or catastrophes. Also discussed during the verification phase were aspects of the effect of placement of the energy source parameters based on their electrical output and their corresponding techno-economic impact on the overall life cycle of the project.

4.2.3.1 Actions towards improvements from Phase III:

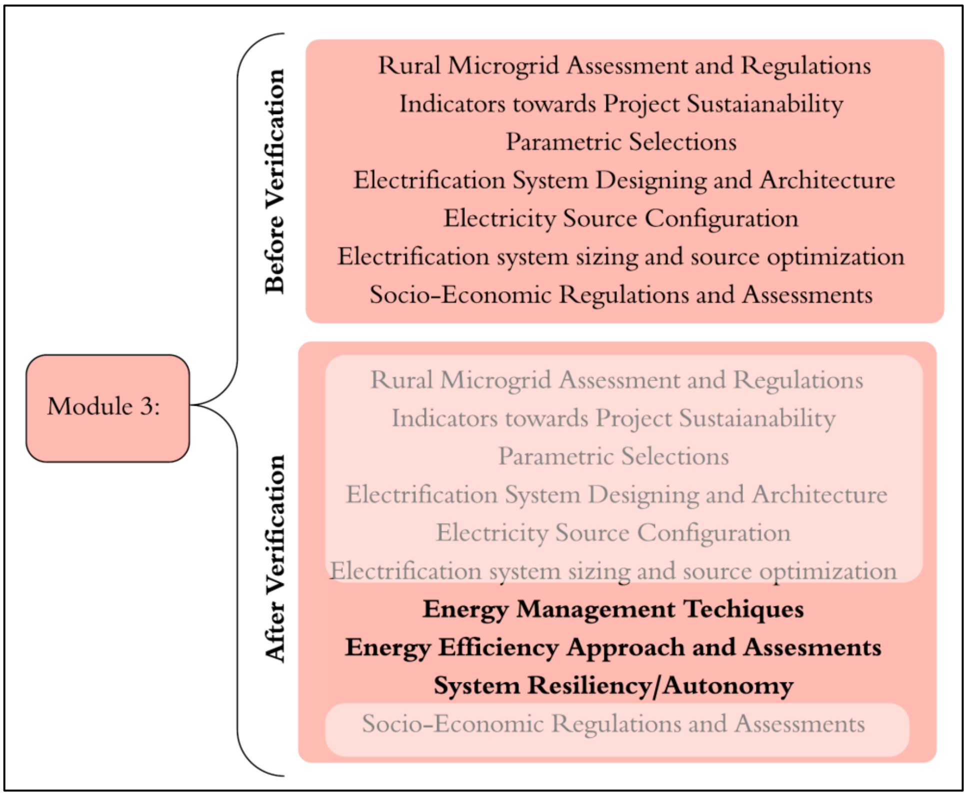


Fig 4.7: Comparison of Improvements (in bold) in Module 3, after the verification process

Fig 4.7 illustrates the way towards improving Module 3 of the CF, which laid importance on the TEA. During this phase, measures were undertaken to ensure the system efficiency is improved by judicious selection of the system parameters and ensuring design safety factors for load growth cases over the project life cycle. Also, factors such as the load variability and sensitivity analysis provide for system redundancy. The outcome of the verification phase involved levels of discussions and improvement factors, which finally led to reducing the net present cost of the system (NPC) to one-third of the cost of the systems previously designed, in addition to ensuring uniform electrification, and a system autonomy of a minimum of 72 hours. The details of the validation process are discussed in Chapter 5.

4.2.4 Verification Phase IV:

The concluding phase of the verification process involved the two taskforce committees "Energy Use in Off-grid Applications" and the "Microgrids Pre-feasibility toolkit" under the IEEE SESDC, to "**substantiate the entire process flow of the design of rural microgrid systems"** based on the developed CF. The ideology underlying this phase of the verification was an assurance of the application of the framework for practical implications in the real-world scenario for future microgrid assessments and developmental activities. As such, the verification of the inclusion of the modules for improving the TEA and further validation of the improved TEA was the agenda for the closed room discussion during the panel session, constituting the experts and a varied audience.

The process flow diagram, as seen in Fig 4.8, explains the various stages at which the modules established within the framework can be effectively utilized for improving the off-grid microgrid deployment scenario. Also, the significance of the process flow diagram established as a flowchart can aid in the further development of a toolkit for remote microgrid assessments. The vision behind developing the toolkit using applicable software and programs is the enhancement of the capacity of energy-deprived communities with limited skills and knowledge in sustainable energy issues while aiding the system developers to support microgrid investments.

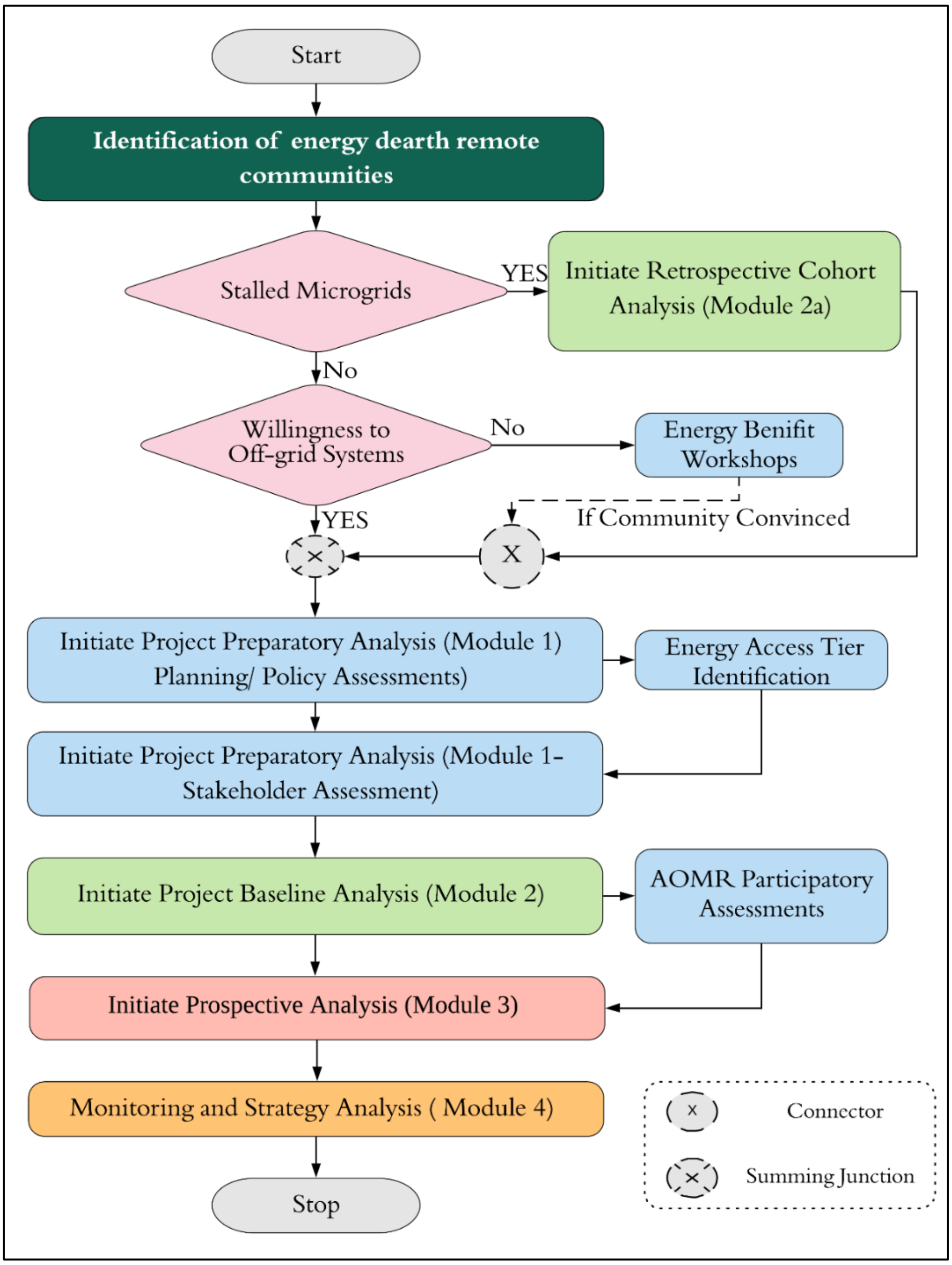


Fig 4.8: Process-flow diagram showing incorporation of modules post Phase IV of research verification

The process flow for the diagram shown in Fig 4.8 starts with identifying the regions/locations having energy (electricity) crises. The locations devoid of electricity access were categorized in two scenarios:

- Scenario 1: Complete absence of decentralized electrification systems
- Scenario 2: Mal-functioned/stalled decentralized electrification systems

The first case considers the complete absence of any off-grid systems available for electricity provisions. On identification of the cause of electricity dearth in the community, an essential step for involving the community arises in order to understand their interest/willingness to off-grid microgrid systems. This step can be accompanied by training sessions/workshops to ensure the community dwellers are informed of the advantages of energy provisions. The scenario for workshops can be taken into consideration for extreme isolated islands/communities without any knowledge of energy benefits. The workshops can contain information outlining the principles of the UN Sustainable Development Goals, their inter-relations, alliance and benefits associated with clean energy access. On attaining the community approval for willingness to access electricity, the following activities, in ways of details mentioned in the modules, can then effectively function. However, during the process, certain features of assessing the energy tier access, satisfactory project developmental and regulatory activity assessments, along with project monitoring and reports constitute the essentials.

The second case considers a scenario where the energy dearth in the communities is a result of the underpinnings or the failure of the microgrids leading to a non-functional state. The assessment activities (like the case assessments in Chapter 2) can be enforced through Module 2(a) of the CF. On identification and reporting of the issues responsible for the failure, modules 1, 2, 3, and 4 can be incorporated to ensure the stalled microgrids attain normalcy and can further aid in scaling up off-grid microgrid deployments in the remote communities.

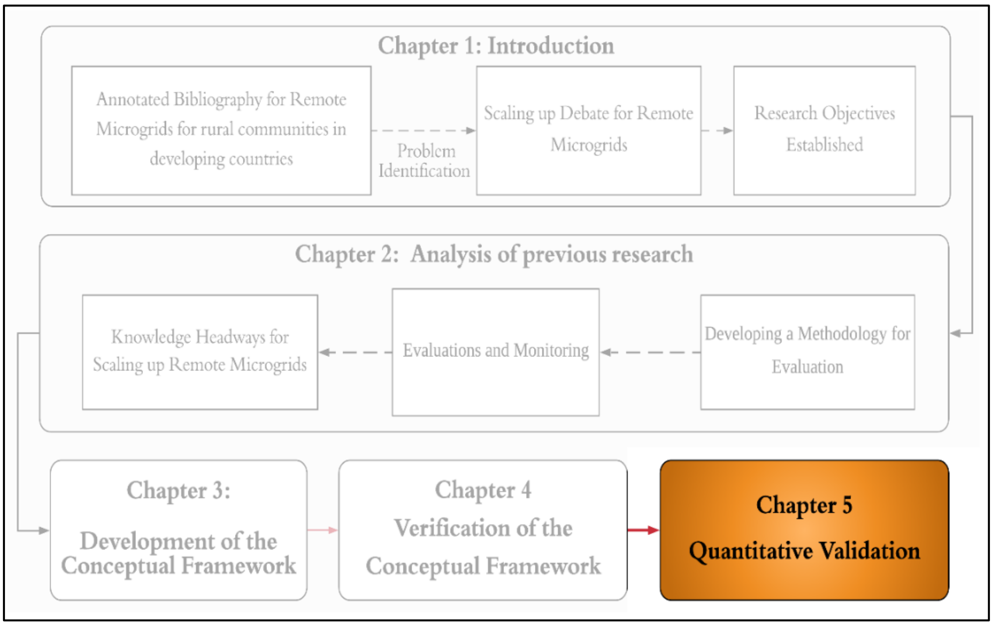
4.3 Chapter Summary

This chapter highlights the verification of the conceptual framework developed in Chapter 3. The verification of the framework was accomplished by engaging a focus group of similar interests in sustainable energy developments for rural communities. Also, the present chapter indicates the four stages of the verification conducted over the timeline from April 1, 2018, to August 31, 2019.

Based on constructive feedback from the expert panel, the framework was modified at each phase ensuring transparency, credibility, and the standard of the research findings. The chapter concludes by outlining the process flow of the modules developed in the CF post the various phases of the verification process. The following chapter delves into a quantitative validation of the framework by undertaking a case study for a developing country context.

Chapter 5

Quantitative Validation



In the previous chapter, the CF was verified, and a flow diagram explaining the process/pattern flow of the framework was established. Based on the verification results, Chapter 5 further investigates the credibility of the CF by undertaking a quantitative research approach (specifically in alignment with Module 3 of CF). The validation method has been classified based on the engineering research classification approach, as explained in [174]. Based on the research validation approach, the present chapter comprises of non-experimental quasi-experimental validation of a framework design/model using a computational simulation tool and a case study of a remote village in India. The computational tool used for the simulation was HOMER Pro[13], a globally accepted standard tool used in industry and academia for optimizing microgrid designs for TEA of decentralized community electrification and islanded utilities. The simulation tool follows a strategy for optimizing systems based on feasible configuration sorted by net present cost (NPC) of the system for a microgrid location selected for the assessment purpose. The following reasons guided the selection of a case study in an Indian context:

- The rural electrification scenario in India indicates a lack of access to essential electrification for the majority of the remote population affecting improvements in the overall social aspects and well-being of the people [175],
- Challenges in establishing microgrid project deployments due to financial issues and the lack of business models as indicated in Chapter 2,

Two scenarios were undertaken and compared using the same computational tool and the software version to situate the improvements in the design for TEA, based on the CF developed. In the first scenario, the current approach for TEA was utilized to design a hybrid renewable energy source microgrid. Further, in the second scenario, a renewable energy source based microgrid was designed for a similar location, while considering the aspects of the CF developed after the framework verification stages. The next section comprises the

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[13]https://www.homerenergy.com/products/pro/index.html

description of the site selected and the availability of energy resources in the location.

5.1 Location Description and Resource Assessment

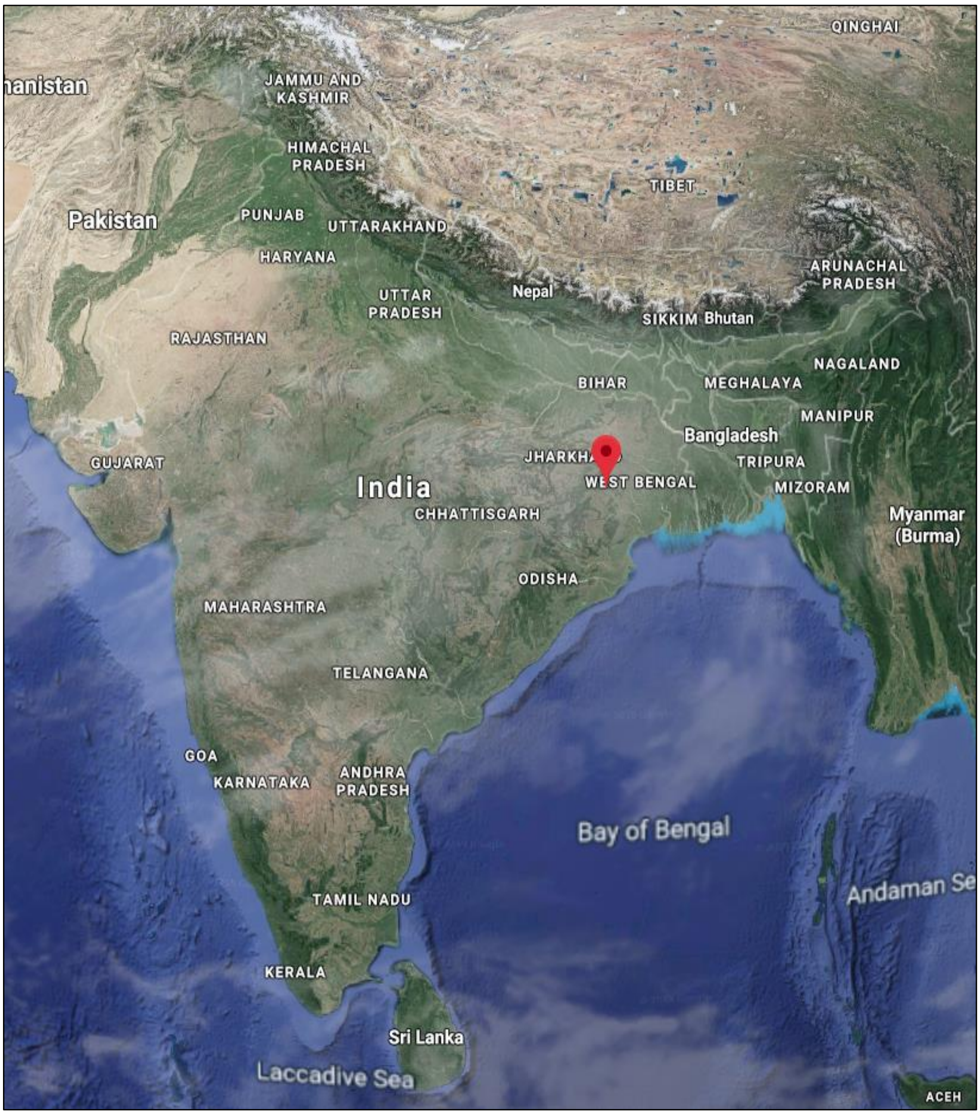

Fig 5.1: Illustration of the site location [176]

The remote location selected for the case study is the village Sapra, having a geographical coordinate of (22°47′N 86°12′E) in the provincial district of West Singhbhum, in the state Jharkhand, India. The village is at an elevation of 159 meters above sea level in the eastern part of India, as shown in Fig 5.1. The selected site distinctly experiences prolonged dry spells of summer (March – October), followed by winters (November-February). The village location is approximately 26 kilometres from Jamshedpur, the third-largest city in eastern India. The city is renowned for the Tata Iron and Steel Company, and the Tata Motors automobile industry. Jamshedpur is the most developed and the cleanest city in eastern India, with adequate facilities for electricity and a decent standard of living [177]–[179]. However, the village Sapra, separated from Jamshedpur by river Doumani, remains in a state of poverty, lacking both in electricity infrastructure and community development. Also, a land dispute between the state and the central government hinders bridging the electricity access gap between the city and village populations.

Considering the adversities and unavailability of centralized grid access to the village, a decentralized approach for electricity provision is an alternative solution. The topography of the selected village being at a higher altitude owing to its plateau terrain provides ample scope for solar and wind energy utilization for power generation. The solar irradiance (kW/m^2), ambient temperature, peak sun hours (PSH), and the wind data has been sourced from NASA Surface Meteorology [180]. The highest PSH of 6.40 is obtained in April while the lowest PSH value of 4.08 recorded in December, with a scaled annual average of 5.01 (kWh/m^2/d) and an average clearness index of 0.541, as shown in Fig 5.2 below. The selected location experiences high temperatures and prolonged dry seasons, with the maximum temperatures recorded as 46˚C in June. Considering the effect of high ambient temperature on the proposed microgrid system is, therefore, essential. The annual average wind speed for the location has been recorded as 2.39 m/s, as shown in Fig 5.3, with an anemometer height at 50 meters. The assessments of variability in the resources for the selected site in the thesis have been distilled to adhere to the specific needs of the analysis; nevertheless, detailed assessments have been presented in Appendix III.

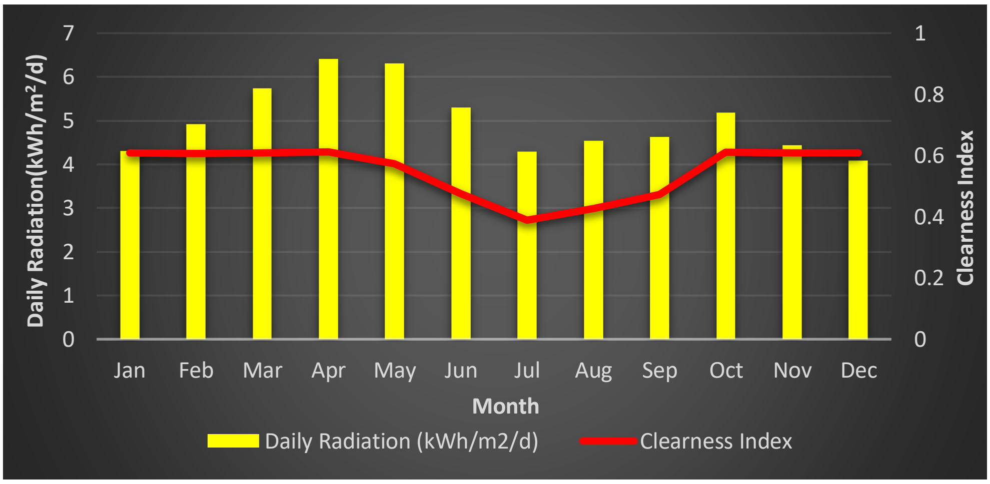

Fig 5.2: Solar Resource Assessment for the location

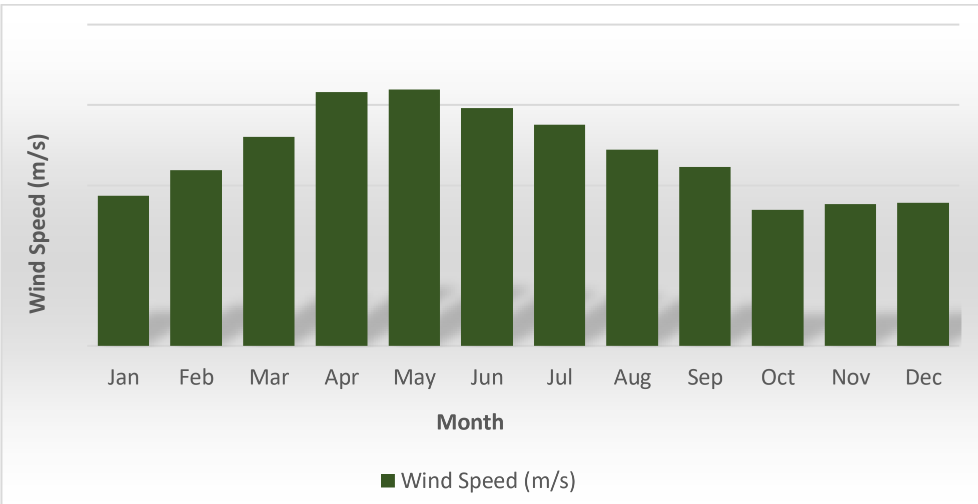

Fig 5.3: Wind Resource Assessment for the location

5.2 Load Classification for the Remote Community Electrification

A load profile estimation is a backbone for any TEA of microgrid. In order to create a load profile, however, it is crucial to understand the lifestyle of the dwellers, their electricity needs, and their energy usage pattern. Understanding the influence of electricity on the lifestyle of people, a lower electrical load factor for the remote communities debars the village dwellers to augment their overall social well-being [181], [182]. In order to ensure the development of the social well-being of the dwellers, therefore, a load estimation pattern has been strategically distributed as an improvement in the electrical load factor in this thesis. Strategic distribution of load has ensured uniform electricity access catering to the varied needs of people for holistic community development and well-being. In view of this, the electrical load for the rural community has been classified into three categories:

- High Priority Load (HPL) – This includes electrical load for the domestic households, a health centre, and a primary school.
- Medium Priority Load (MPL) – Comprises of the community street lights, community toilets, a community hall, and shops.
- Deferrable Load (DL) – This load has been categorized for the electrical loads that require a certain amount of energy within a given time period (in this case, the agricultural load).

Furthermore, based on the load classification and the lifestyle of the dwellers, for their electricity usage pattern, a day-to-day variation along with a time-step-to-time-step variation in the capacity utilization was considered. The mechanism for adding day-to-day and time-step-time-step variability is given by a perturbation factor (α), as shown in Eq 1:

$$\alpha = 1 + \delta_d + \delta_{ts} \qquad \text{.........Eq 1}$$

Where,

δ_d= daily perturbation factor, δ_{ts}= time step perturbation factor

5.3 Parametric Selections for System Modelling

A necessary step underlying the identification of the resources and the load estimation lies in the selection for the system parameters. The case study focusses on a hybrid renewable energy system (HRES) microgrid, using a 100 percent renewable fraction, as a useful technology for electricity providers. The HRES comprise the solar and the wind energy as electricity generation sources, along with a battery storage system (BSS) and a converter. To compare the TEA approaches, similar manufacturing type and model for the PV panels (PVs), wind turbines (WTs), BSS, and the converter were considered. The output power of the PV array module (P_{PV}) considered for the HRES can be calculated from the following equation:

$$P_{pv} = n * R_{pv} * D_{pv}\left[\frac{G_s}{G_{s,STC}}\right]\left[1 + \alpha_p\left(T_c - T_{c,STC}\right)\right] \qquad \text{......Eq 2}$$

Where,

$$T_c = T_a + \left[\frac{NOCT - 20°}{0.8}\right] \qquad \text{..........Eq 3}$$

R_{pv} = Rated capacity of PV in kW, D_{pv} = Derating factor (%), G_s = Solar radiation incident on PV array (kW/m^2), $G_{s,STC}$= Incident radiation at STC, α_p = temperature coefficient of power, T_c = PV cell temperature, $T_{c,STC}$ = PV cell temperature under STC, $NOCT$ = Normal operating cell temperature, T_a = Ambient cell temperature.

The values of G_s and T_a were obtained from NREL [158], [183]. Consecutively, the values of NOCT, D_{pv} and η_{STC} selected were 47°, 90% and 13% respectively. The power losses in the system may arise, pertaining to factors such as aging of the PV, dust accumulation on PV modules, wiring losses, shadow effect, or cloud passing.

To overcome the system losses, the usage of an additional energy source as wind for power generation will also result in the longevity of the life of the BSS. The boost in the lifetime of the BSS will have a direct impact on the overall economic aspect of the microgrid project. The generation of power from a wind turbine, however, depends on the availability of the wind, which is location dependent. Since the site selected for the case study is suitable for the availability of wind, the factors such as the hub height and the variation of the wind speed with subsequent variation in hub height play a significant role. The variation of wind speed at different height is given by a logarithmic profile if the wind speed is proportional to the logarithm of height above the ground. Here, the ratio of the wind speed at hub height to the anemometer height is expressed in the following equation:

$$\frac{V_{hub}}{V_{anem}} = \frac{ln\left(\frac{Z_{hub}}{Z_o}\right)}{ln\left(\frac{Z_{anem}}{Z_o}\right)} \qquad \text{.........Eq 4}$$

Where,

$Z_{hub} =$ Hub height of wind turbine (m), Z_{anem} = Anemometer height (m), V_{hub} = the wind speed at the hub height of the wind turbine [m/s], V_{anem} =the wind speed at anemometer height [m/s].

Thereafter, the power-law profile of the wind speed at different heights, where α is the power-law exponent, is expressed as in Eq 5.

$$\frac{V_{hub}}{U_{hub}} = \left[\frac{Z_{hub}}{Z_{anem}}\right]^{\alpha} \qquad \text{.........Eq 5}$$

Where,

α = Power law exponent associated with the wind power calculation

For this study, the wind turbine generator considered has a power curve, as shown in Fig 5.4.

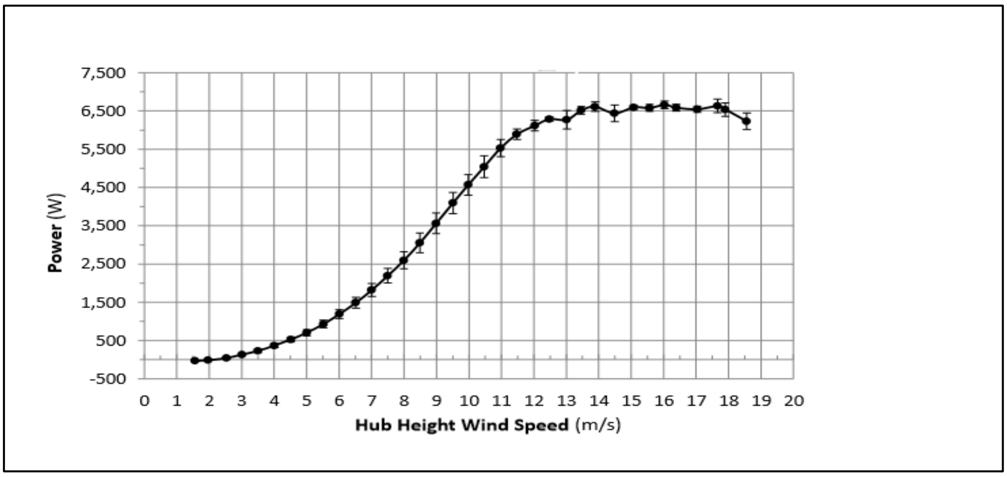

Fig 5.4: Power Curve of Wind Turbine

The power curve by the air density ratio is expressed as:

$$\mathrm{Pc_{WTG}} = \left[\frac{\rho}{\rho_o}\right] \mathrm{Pc_{WTG,STC}} \qquad \text{Eq 6}$$

Where,

$\mathrm{Pc_{WTG}}$= the wind turbine power output (kW), $\mathrm{Pc_{WTG,STC}}$ = the wind turbine power output at STP (kW), P= the actual air density (kg/m^3), ρ_{0}= the air density at standard temperature and pressure (1.225 kg/m^3)

The battery storage system (BSS) considered for an off-grid system for any remote or island electrification plays a significant role in determining an overall technical and economic aspect for the entire project lifetime. As such, proper sizing of the BSS is a determining factor for any microgrid project. The $\mathrm{B_{ss}}$ sizing can be expressed as:

$$\mathrm{B_{ss}} = \frac{\mathrm{LD}}{\eta_{rt} * \mathrm{DOD} * \mathrm{B_v}} \qquad \text{Eq 7}$$

Where,

LD=Load Demand, η_{rt}= Round Trip Efficiency, DOD= Depth of Discharge, B_v= Battery System Voltage

For this study, the DOD max, which is the maximum depth of discharge, was considered as 0.7. The constraints for the Bss are based on the following equations:

$$B_{ss}(\text{min}) \leq B\_ss \leq B_{ss}(\text{max}) \qquad \text{Eq 8}$$

$$B_{ss}(\min) = (1 - DOD_{max}) * B_{ss}(max) \quad \text{Eq 9}$$

As per the criteria mentioned above, the Bss (min), which is the minimum state of charge for the battery, was considered as 30 percent of the Bss (max). Also, the BSS considered for this study has a lifetime throughput of 1075 kWh. The capacity curve and the lifetime curve of the BSS used for the HRES, are shown in Fig 5.5, and Fig 5.6 was derived from the experiment.

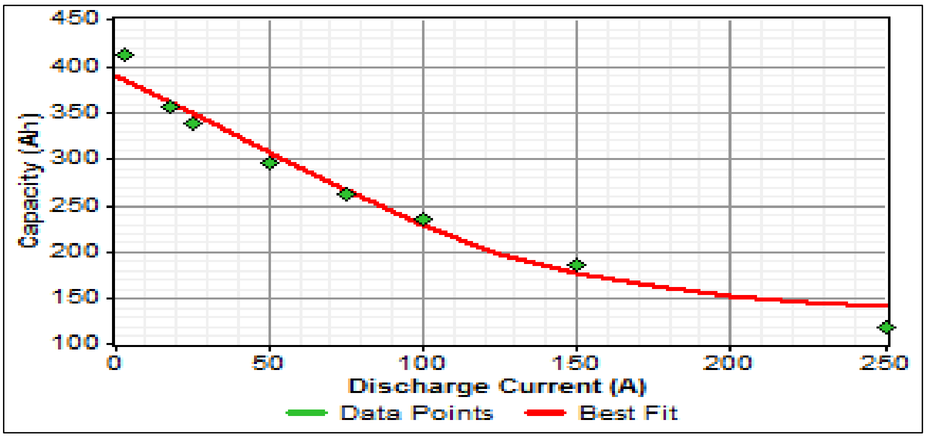

Fig 5.5: The capacity curve of the storage unit

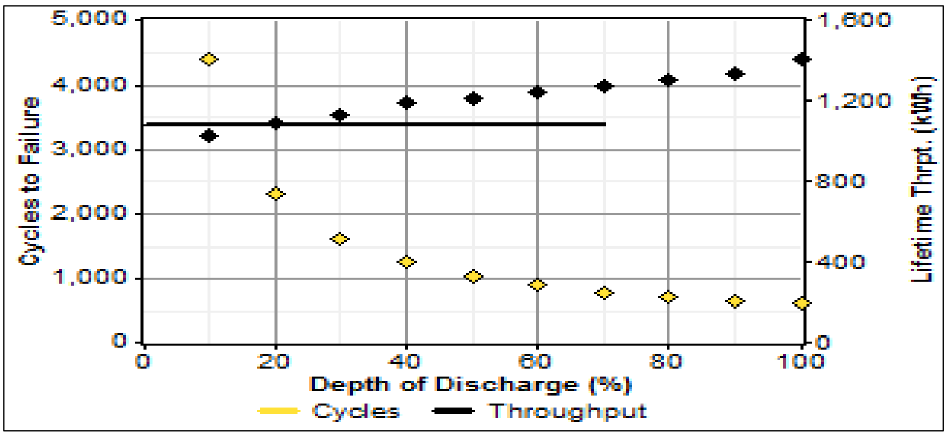

Fig 5.6: Lifetime Curve of the storage unit

For the economic feasibility assessment for microgrids, it is vital to ascertain the component cost for the selected system parameters. Here, the cost of the system was eventually considered in terms of the initial capital cost, replacement cost, and the maintenance cost of the system, which are provided in Table 5.1 as per the 2018 market values of the components available from consultation with the commercial entities.

Table 5.1: Parametric systems components with corresponding costs

System Components	Type of Cost (USD)		
	Capital	Replacement	Maintenance
P V Array	1330	1330	10
Wind Turbine	1800	1500	20
Battery Storage System	170	130	5
Inverter	300	300	0

5.4 Scenario 1: TEA Based on Current Practices (without implementing the Conceptual Framework)

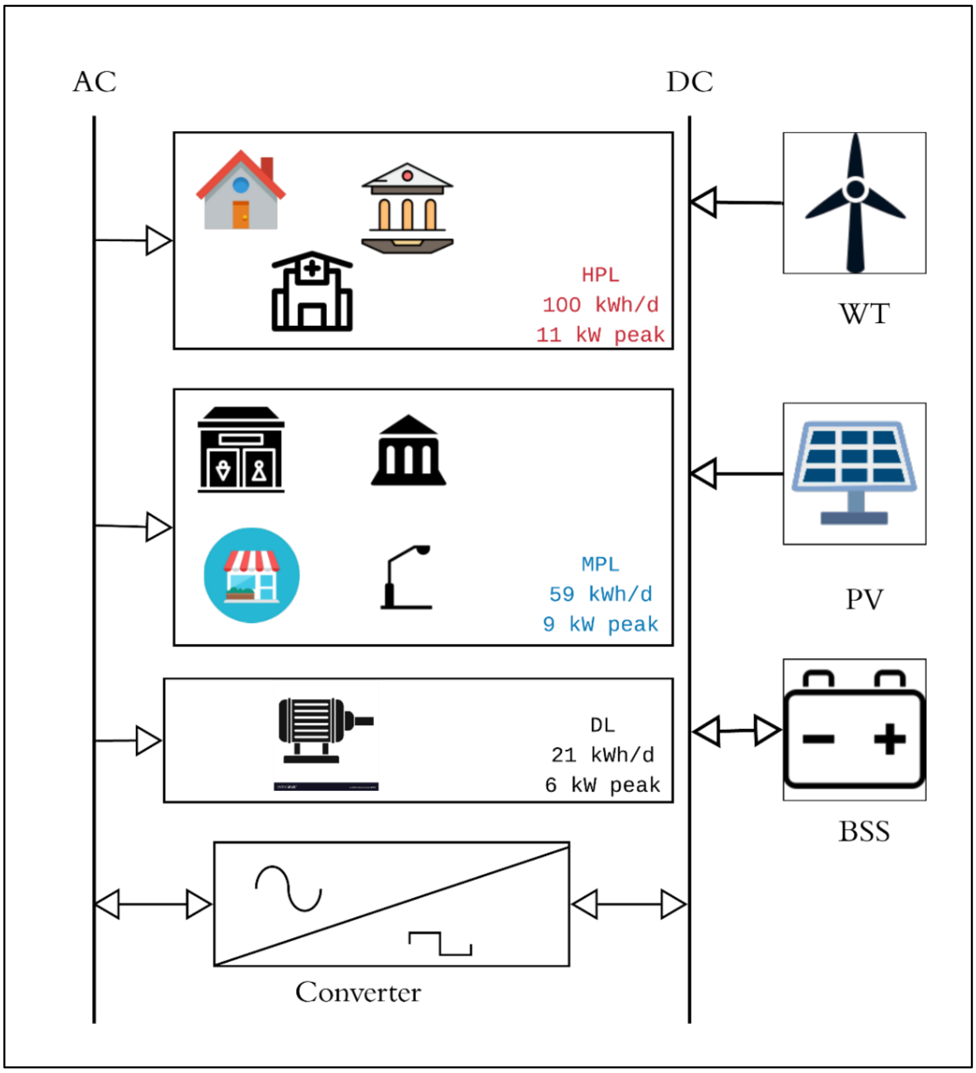

Fig 5.7: The architecture of a Hybrid Renewable Energy based Microgrid for remote electrification

Based on the load classification for electrifying a remote community, an HRES model, as shown in Fig 5.7, has been designed. The HPL comprises of 20 households, a primary school for accommodating students in the age group of 6 to 14 years, with class sizes of approximately 40 combined age group students, and a health centre. The MPL comprises of the streetlights, community toilets, shops and a community hall, while the DL comprises the agricultural load (water pump). In order to design a load profile for a time period of 24 hours and based on the variations in the seasons, it is essential to determine the lifestyle pattern of the dwellers and the appliance usage time for various load types. It is this researcher's observations that for the households, the electrical appliances typically comprise three CFL bulbs (20W each), two incandescent bulbs (40W each), two ceiling fans each 60W, a table fan (40W), a radio (10W), a mobile charger of 5W and a 60W television set as tabulated in Table 5.2. The appliance description and the ratings are based on the literature as previously considered by the researcher in published articles/reports [67], [127].

Table 5.2: Appliances Description for a single household

Household Electrical Appliances	Watts	Units of Appliances
CFL	20	3
Incandescent Bulb	40	2
Ceiling Fan	60	2
Table fan	40	1
Radio	10	1
Mob Charger	5	1
Television	60	1

The village selected comprises of dwellers mostly engaged in contractual jobs in the nearby city, and few earn their living as farmers growing seasonal vegetables. As such, the people in the village wake up by 5 am, where the farmers leave their houses by 6 am for their farming activities, while the remaining contractual workers leave by 7 am. The housemakers carry on their daily household activities, and the children leave for school by 8 am. The electricity usage pattern, as such, is minimal during the daytime from 8 am to mid-noon. Thereafter, the children and the farmers return for their afternoon meals leading to an increase in electricity consumption for an hour or two. Again, post-lunch, the peasants leave for work, and housemakers dwell the house from 2 pm onwards. The peak load is observed from 6 pm onwards when the entire family is in the house, maximizing the energy use for various activities. However, from experience, the electricity usage pattern for seasonal variations is tabulated in Table 5.3. Following this, a 24-hour load profile for two seasons (summer and the winter) is plotted in Fig 5.8, based on the observation made.

Table 5.3: A 24-hour electricity usage pattern for 20 households

Hour	A load profile of Single House (kW)		Load Profile of 20 houses (kW)	
			Summer (Mar-Oct)	Winter (Nov –Feb)
00:00 - 01:00	0.18	0.085	3.6	1.7
01:00 - 02:00	0.18	0.085	3.6	1.7
02:00 - 03:00	0.18	0.085	3.6	1.7
03:00 - 04:00	0.18	0.085	3.6	1.7
04:00 - 05:00	0.19	0.085	3.8	1.7
05:00 - 06:00	0.165	0.12	3.3	2.4
06:00 - 07:00	0.165	0.12	3.3	2.4
07:00 - 08:00	0.165	0.12	3.3	2.4
08:00 - 09:00	0.165	0.065	3.3	1.3
09:00 - 10:00	0.165	0.065	3.3	1.3
10:00 - 11:00	0.15	0.065	3	1.3
11:00 - 12:00	0.19	0.065	3.8	1.3
12:00 - 13:00	0.225	0.065	4.5	1.3
13:00 - 14:00	0.17	0.125	3.4	2.5
14:00 - 15:00	0.21	0.125	4.2	2.5
15:00 - 16:00	0.21	0.125	4.2	2.5
16:00 - 17:00	0.24	0.125	4.8	2.5
17:00 - 18:00	0.27	0.125	5.4	2.5
18:00 - 19:00	0.315	0.21	6.3	4.2
19:00 - 20:00	0.315	0.21	6.3	4.2
20:00 - 21:00	0.315	0.21	6.3	4.2
21:00 - 22:00	0.25	0.21	5	4.2
22:00 - 23:00	0.19	0.175	3.8	3.5
23:00 - 00:00	0.18	0.085	3.6	1.7

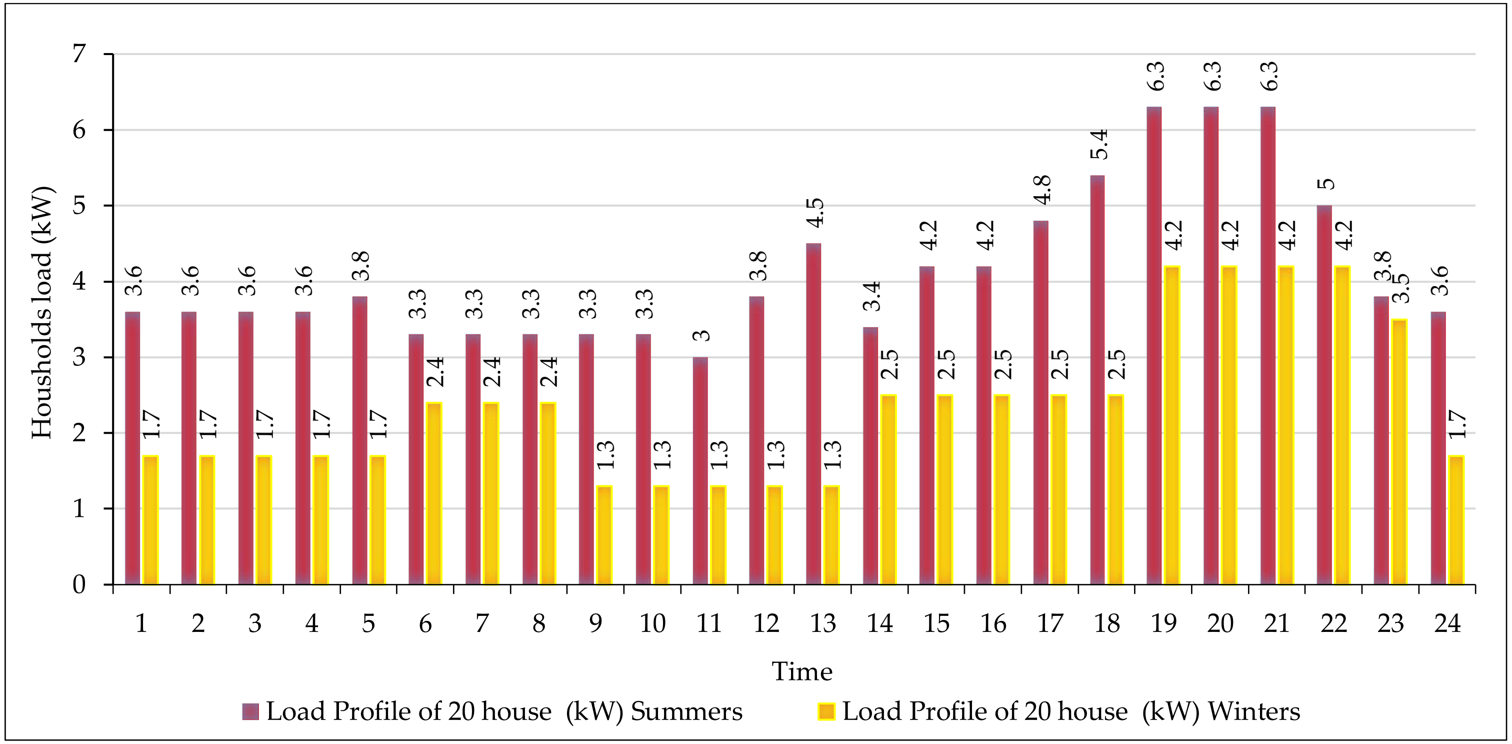

Fig 5.8: Seasonal variation-based load profile for 20 households in the village

Similarly, the health centre was considered functional from 7 am - 7 pm and comprised of appliances as tabulated in Table 5.4. Also, the electricity usage pattern with the seasonal variations over the year, for a 24-hour load profile is shown in Fig 5.9. The appliance description and the ratings are based on the literature as previously considered by the researcher in published articles/reports [67], 127].

Table 5.4: Appliances Description for health centre

Electrical Load	Watts	Total units
CFL	20	6
Incandescent Bulb	60	1
Ceiling Fan	60	5
Refrigerator	300	1
Mob Charger	5	1

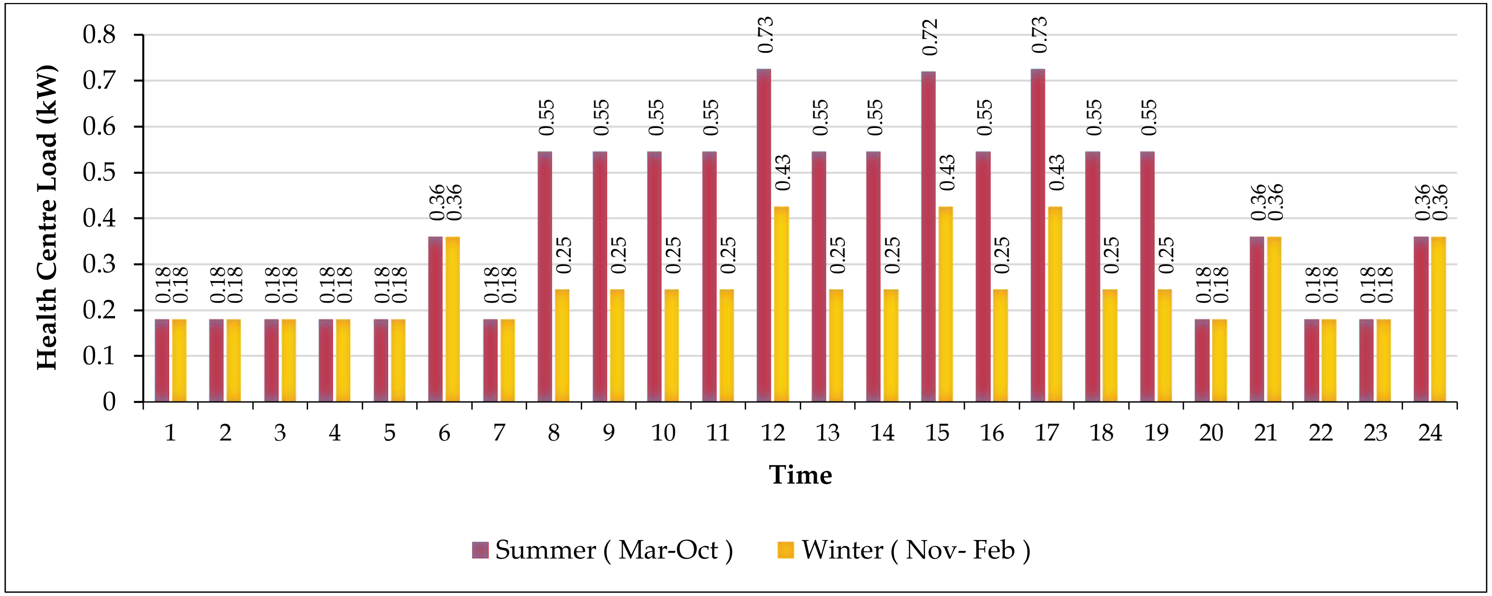

Fig 5.9: Seasonal variation-based load profile for the health centre

Furthermore, the primary school was operating on a fixed time, enabling a consideration for a random variability of 5 percent for designing the load profile. For instance, the school starts at 8 am, where the electrical load constitutes the lighting and cooling load in the form of CFLs and ceiling fans during summers. Additionally, a desktop computer adds to the load profile with variations in the mobile charging unit as when required. The school runs until 4 pm with an hour lunch from 12 pm to 1 pm. In the last hour of school, an ICT session delivered via television was considered every day for designing the load profile. The administrative work of the school is carried out till 5 pm, after which the school closes for the day. While the maximum electrical load is experienced during the school hours, a lighting load was operating in the after-hours of the school as part of security measures to prevent theft and vandalism. The electrical appliances considered for the school are tabulated in Table 5.5 with a 24-hour load profile plotted in Fig 5.10. The appliance description and the ratings are based on the literature as previously considered by the researcher in published articles/reports [67], 127].

Table 5.5: Appliances Description for primary school

Electrical Load	Watts	Units of Appliances
CFL	20	10
Incandescent Bulb	60	1
Ceiling Fan	60	5
Desktop Computer	300	1
Mob Charger	5	1
Television	60	1

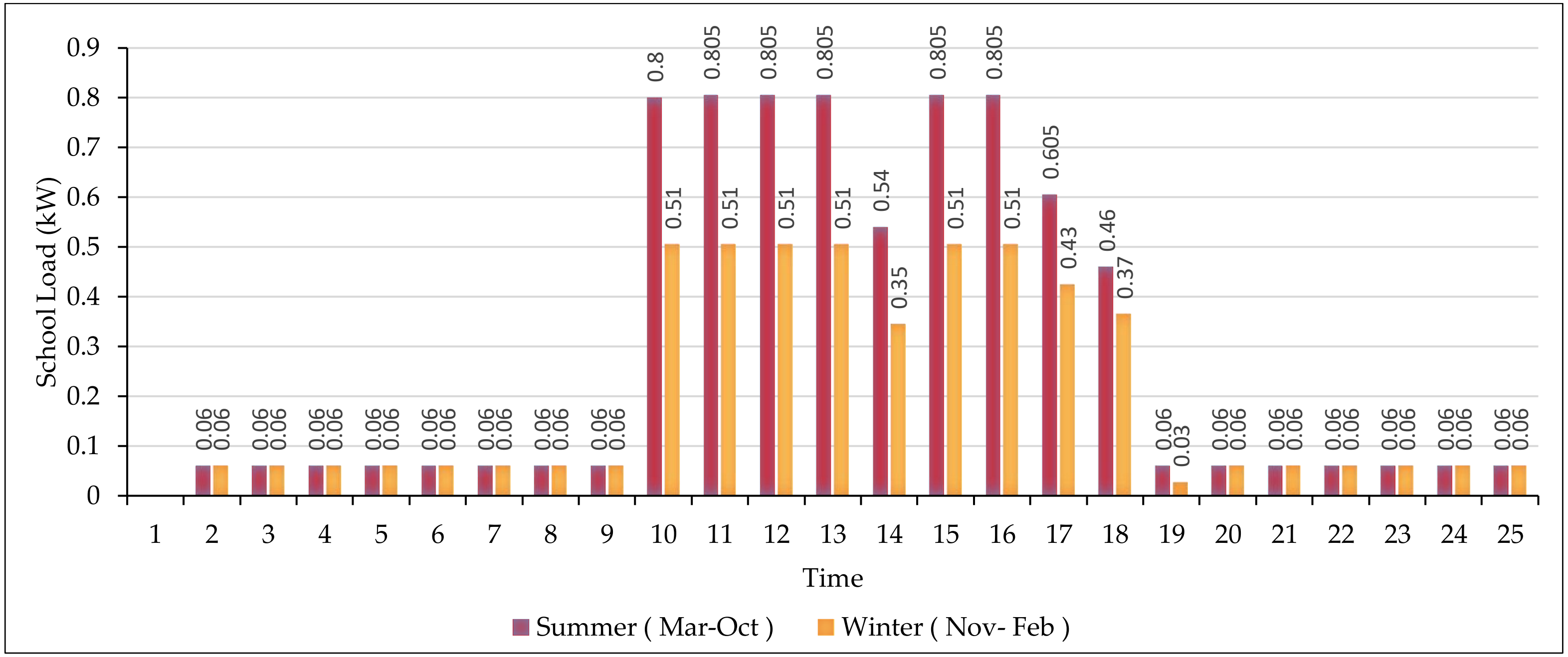

Fig 5.10: Seasonal variation-based load profile for primary school

Following the above considerations, Table 5.6 tabulates the total load for the HPL for two seasons based on the 24-hour load profile, as shown in Fig 5.11.

Table 5.6: A 24-hour electricity usage pattern for HPL

Hour	Total High Priority Load (HPL) kW	
	Summer	Winter
00:00 - 01:00	3.84	1.94
01:00 - 02:00	3.84	1.94
02:00 - 03:00	3.84	1.94
03:00 - 04:00	3.84	1.94
04:00 - 05:00	4.04	1.94
05:00 - 06:00	3.72	2.82
06:00 - 07:00	3.54	2.64
07:00 - 08:00	3.905	2.705
08:00 - 09:00	4.645	2.05
09:00 - 10:00	4.65	2.05
10:00 - 11:00	4.35	2.05
11:00 - 12:00	5.33	2.23
12:00 - 13:00	5.585	1.89
13:00 - 14:00	4.75	3.25
14:00 - 15:00	5.725	3.43
15:00 - 16:00	5.35	3.17
16:00 - 17:00	5.985	3.29
17:00 - 18:00	6.005	2.772
18:00 - 19:00	6.905	4.505
19:00 - 20:00	6.54	4.44
20:00 - 21:00	6.72	4.62
21:00 - 22:00	5.24	4.44
22:00 - 23:00	4.04	3.74
23:00 - 00:00	4.02	2.12

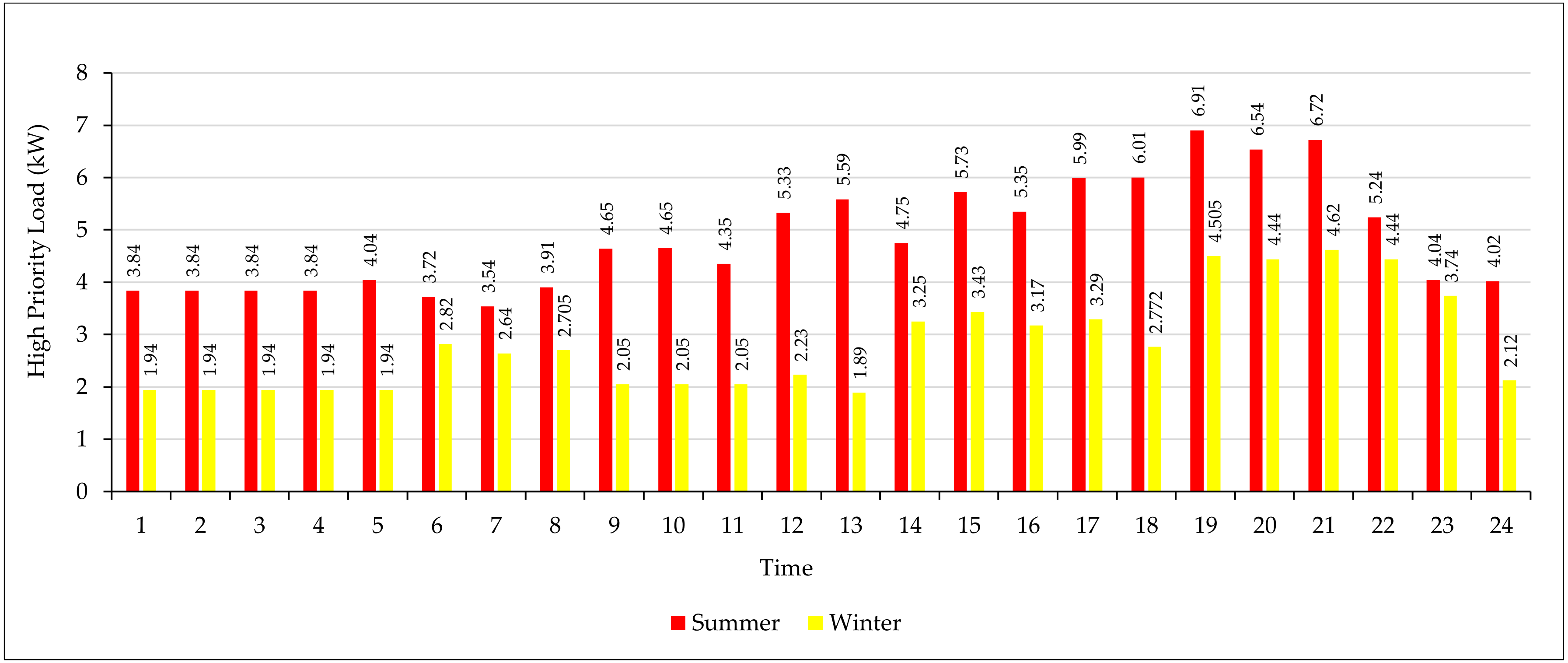

Fig 5.11: Seasonal variation-based load profile for HPL

It should be stated that the focus of the MPL was mainly on electricity access for the community aspects. The MPL covered the various aspects of the SDGs, such as community halls for (SDG 5, SDG8, SDG 10, SDG 11, SDG 16 and SDG 17), streetlights for (SDG 3, SDG 8, and SDG 11), and community toilets for SDG 6. Similarly, shops were considered to enable economic growth (SDG 8). Thereafter, a similar approach as practised for the HPL was implied for the MPL, where, the appliances were selected, and their usage pattern was determined based on the seasonal variations as tabulated in Table 5.7. Accordingly, a 24-hour load profile was for the MPL was plotted, combining all the loads, as shown in Fig 5.12.

Table 5.7: A 24-hour electricity usage pattern for various loads and total MPL

Hour	Streetlights		Community Toilets		Community Hall		5 shops		Total Medium Priority Load (MPL) kW	
	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter
00:00 - 01:00	3.6	3.6	0.3	0.3	0.06	0.06	0.1	0.1	4.06	4.06
01:00 - 02:00	3.6	3.6	0.3	0.3	0.06	0.06	0.1	0.1	4.06	4.06
02:00 - 03:00	3.6	3.6	0.3	0.3	0.06	0.06	0.1	0.1	4.06	4.06
03:00 - 04:00	3.6	3.6	0.3	0.3	0.06	0.06	0.1	0.1	4.06	4.06
04:00 - 05:00	3.6	3.6	0.3	0.3	0.06	0.06	0.1	0.1	4.06	4.06
05:00 - 06:00	3.6	3.6	0	0.3	0	0.06	0.1	0.1	3.7	4.06
06:00 - 07:00	0	0	0	0	0	0	0.1	0.1	0.1	0.1
07:00 - 08:00	0	0	0	0	0	0	0.575	0.275	0.575	0.275
08:00 - 09:00	0	0	0	0	0	0	0.575	0.275	0.575	0.275
09:00 - 10:00	0	0	0	0	0.59	0.21	0.575	0.275	1.165	0.485

10:00 - 11:00	0	0	0	0	0.59	0.21	0.575	0.275	1.165	0.485
11:00 - 12:00	0	0	0	0	0.59	0.21	0.575	0.275	1.165	0.485
12:00 - 13:00	0	0	0	0	0.59	0.21	0	0	0.59	0.21
13:00 - 14:00	0	0	0	0	0.59	0.21	0	0	0.59	0.21
14:00 - 15:00	0	0	0	0	0.59	0.21	0.575	0.275	1.165	0.485
15:00 - 16:00	0	0	0	0	0.59	0.21	0.575	0.275	1.165	0.485
16:00 - 17:00	0	0	0	0	0.59	0.21	0.575	0.275	1.165	0.485
17:00 - 18:00	0	3.6	0	0.3	0.59	0.21	0.575	0.275	1.165	4.385
18:00 - 19:00	3.6	3.6	0	0.3	0.65	0.27	0.575	0.275	4.825	4.445
19:00 - 20:00	3.6	3.6	0.3	0.3	0.65	0.27	0.575	0.275	5.125	4.445
20:00 - 21:00	3.6	3.6	0.3	0.3	0.06	0.06	0.1	0.1	4.06	4.06
21:00 - 22:00	3.6	3.6	0.3	0.3	0.06	0.06	0.1	0.1	4.06	4.06
22:00 - 23:00	3.6	3.6	0.3	0.3	0.06	0.06	0.1	0.1	4.06	4.06
23:00 - 00:00	3.6	3.6	0.3	0.3	0.06	0.06	0.1	0.1	4.06	4.06

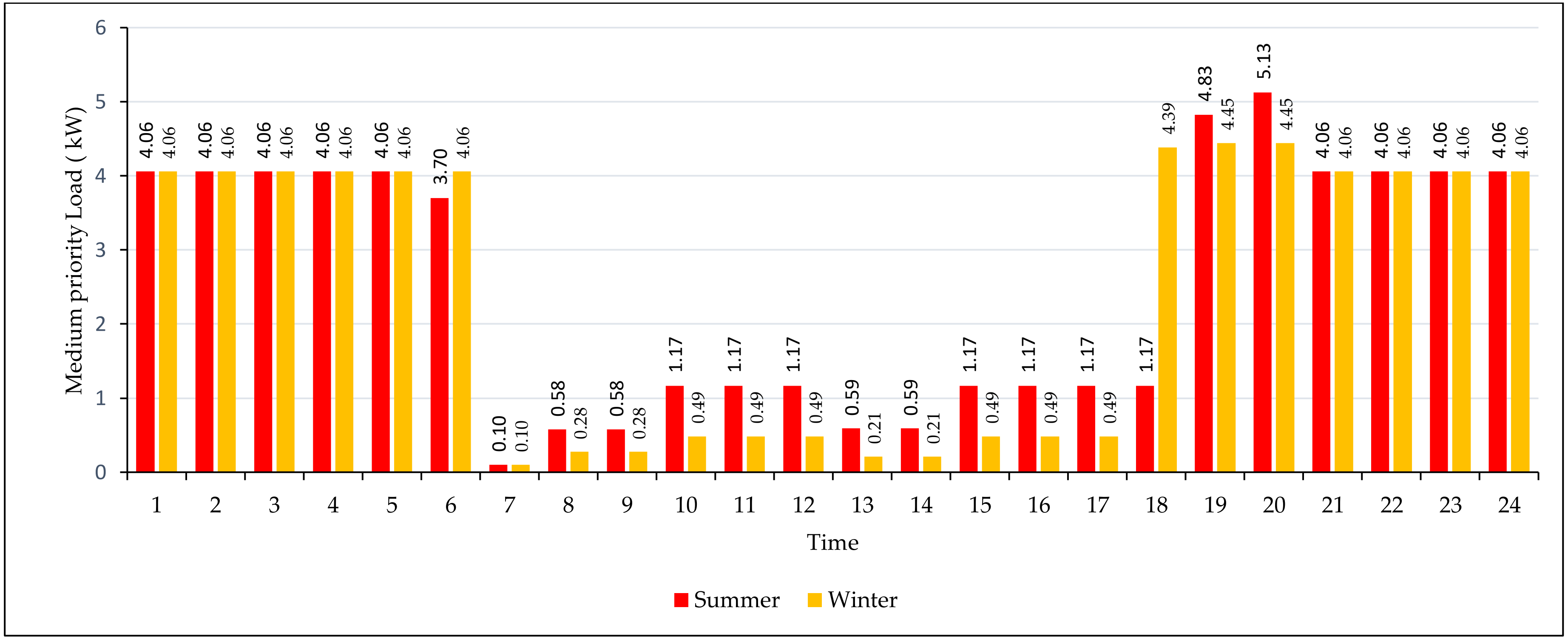

Fig 5.12: Seasonal variation-based load profile for MPL

5.4.1 Results and Discussions

The analysis of the modelled HRES can be broadly classified into two phases, namely a technical and an economic assessment. The technical aspects are based on the specifications as per the IEC/TS 62257 standards for rural electrification [167], [169], [170], [184]. The economic aspects of the case study include an annualized and net present cost of the system based on the system components and resources selected. The importance of economic assessment lies in understanding the aspects of the economic feasibility of the microgrid infrastructure, enabling it to be implemented on a practical level. This could be a step towards attracting investors, utilities and the nodal agencies to set up an off-grid electrification infrastructure where the centralized grid extension fails. The economics of any microgrid system is determined by the system's overall net present cost (NPC), which is determined by the difference between the present existing value of all the costs incurred over a lifetime, and the value of the salvage revenue earned over the project lifetime of 25 years, or cost of energy (LCOE), given by average cost per kWh of useful electricity generated by the system.

5.4.1.1 System Analysis

In order to achieve the goal of providing energy access to the community, the HRES was modelled for an average scaled load of 100 kWh/day with a peak load demand of 11 kW for the HPL, followed by an average load demand of 59 kWh/day with a peak load demand of 11 kW for the MPL, and scaled load profile of 21 kWh/day with a peak demand of 6 kW for the DL. An overall random variability for the model considered a day-to-day variability of 15 percent with a timestep variation of 20 percent for the entire microgrid model.

The technical results featuring the electrical profile indicated a ratio of 70:30 percent for the total electrical production from the HRES (PV+WT). This result indicated a dominance of energy generated from the PV over WT in the overall electricity generation process. The dominance of a single source energy generation in an HRES demonstrates under-utilization of the energy resources, which indicates a lack of proper energy management from an engineering design perspective. The consumption of the AC primary load (HPL+MPL) comprised 58,222 kWh/yr (88 percent) with the DL as 7,615 kWh/yr (12 percent) of the total electricity consumption of 65,837 kWh/yr. Table 5.8, however, indicates a capacity shortage of 65.4 kWh/y despite an excess electricity generation of 158,249 kWh/yr from the HRES. What this means is that the overall energy efficiency of the system was hindered due to a higher capacity shortage over the excess electricity generated from the system, which further indicates an in-efficient system design/ an inefficient energy management technique.

The BSS for the HRES comprised a total of 388 batteries with a string size of 2 and 194 strings in parallel for a 24 V DC system for the remote microgrid. The BSS had an annual throughput of 35,094 kWh/yr with a storage wear cost of 0.84 $/kWh. The usable nominal capacity of the battery was found to be 272 kWh with a lifetime expectancy of 8 years. The life expectancy of the BSS also indicated the need for battery replacements in every eighth year (i.e., approximately thrice in the overall lifetime period of the project of 25 years). The autonomy of the battery was found to be a maximum of 34 hours.

Owing to the location of the site, and as per discussions with the experts during the verification stages of the research, and autonomy of 72 hours (3 days) is considered suitable for any off-grid electrification scenarios. Further, experiments for improving energy management and obtaining higher system autonomy were conducted by incorporating a sensitivity analysis of the system. The sensitivity analysis was incorporated, by designing the HRES for a higher capacity shortage (in range of 10-50 percent). However, as indicated in Table 5.8, no improvements in energy management and system autonomy for the HRES were obtained. The economic assessment for the system determined an NPC of USD 355,734 and LCOE USD 0.42 (per kWh) for the HRES, as detailed in Table 5.8.

Table 5.8: Optimized Tabulation for TEA, based on Scenario 1 of microgrid assessment.

Capacity Shortage (%)	Architecture				System Economic Analysis (USD)				System Technical Analysis				
	PV (kW)	WT	BSU	Converter Capacity	NPC	LCOE (per kWh)	OpEx	CaPex	Capacity Shortage (kWh/yr)	Electrical Prod (kWh/yr)	Excess Electricity (kWh/yr)	Unmet load (kWh/yr)	Autonomy (hr)
0	105	23	388	20	355,734	0.42	8,251	249,073	65	234,676	158,249	46	34
10	52	7	206	12	178,358	0.23	4,445	120,893	6,646	100,363	29,447	4,919	19.2
20	40	7	170	10	145,350	0.20	3,671	97,891	13,243	82,960	18,244	9,764	15.8
30	32	8	132	10	120,395	0.18	2,944	82,334	19,773	75,051	17,341	15,138	12.3
40	25	10	86	15	98,359	0.17	2,163	70,392	26,412	73,266	23,165	20,886	8.0
50	21	8	66	5	76,987	0.15	1,648	55,682	32,993	59,748	16,088	26,159	6.1

5.5 Scenario 2: TEA based on the developed Conceptual Framework

Scenario 2 of the TEA features the implementation of the developed CF. The various issues pertaining to inadequate load profile modelling, higher system capacity shortage, in-efficient energy management models, and inadequate system autonomy were identified as significant technical constraints for Scenario 1, affecting the popularity of remote microgrid systems. Also, a higher NPC of the system was a critical aspect classified by the experts during the CF verification stage, which is responsible for disinterest in large-scale investments by the private or nodal agencies for off-grid system establishments for energy provisions in the remote/island communities. However, pragmatic efforts in Scenario 2 of the TEA for the remote microgrid assessments, consider improvisations in the following ways:

- An energy-efficient approach for reducing the scaled average load demand per day without compromising the average peak loads;
- Testing various configurations of the system parameters for an appropriate energy system model in ways to achieve an efficient energy management system;
- Ensuring system autonomy is achieved for the microgrid model in order to strengthen the resiliency of the microgrids in events of natural/technical breakdowns; and

- Considering the economic feasibility of the systems based on lower NPC and LCOE to attract investments.

5.6 Improvisations in the Load Profile

Based on the load classification mentioned earlier, similar loads were considered, which consisted of the HPL, MPL, and the DL. The units and the types of appliances were strategically selected following energy-efficient approaches without negotiating with the basic needs of the community dwellers.

The HPL, as discussed before, consists of the 20 households, with a health centre and a primary school. Contrary to the load profile design in the previous case, the present case considered separate weekday and weekend loads for confirming accuracy for a 24-hour profile. The consideration, designing separate load profiles, adheres to the variations in the lifestyle of the dwellers in relation to usage hours of the appliances over the weekend in comparison to the weekdays. The energy-efficient approaches considered during the designing phase of the load profile measures such as replacing the CFL and the incandescent bulbs with LEDs, considering several lighting loads based on standard building specifications for lux/square feet, improved refrigerators for storing vaccines. The details of the electrical appliances for the various loads constituting the HPL are tabulated in Table 5.9, Table 5.10, and Table 5.11, respectively. Based on the appliances used, the load profile for the HPL for two seasonal variations based on a 24-hour load profile is shown in Fig 5.13. Similarly, a 24-hour season variation-based load profile for the MPL constituting the street lights, community toilets, a community hall, and shops for a random day-to-day random variability of 5 percent is shown in Fig 5.14.

Table 5.9: Appliances Description for a single household

Household Electrical Appliances	Watts	Units of Appliances
LED bulbs	9	4
Ceiling Fan	60	2
Radio	10	1
Mobile Charger	5	1
Television	60	1

Table 5.10: Appliances Description for health centre

Health-Centre Electrical Appliances	Watts	Units of Appliances
LED bulbs	9	9
Ceiling Fan	60	5
Vaccine Refrigerator (100 litres)	40	1
Mobile Charger	5	1

Table 5.11: Appliances Description for primary school

School Electrical Appliances	Watts	Units of Appliances
LED bulbs	9	11
Ceiling Fan	60	5
Desktop Computer	250	1
Mobile Charger	5	1
Television	60	1

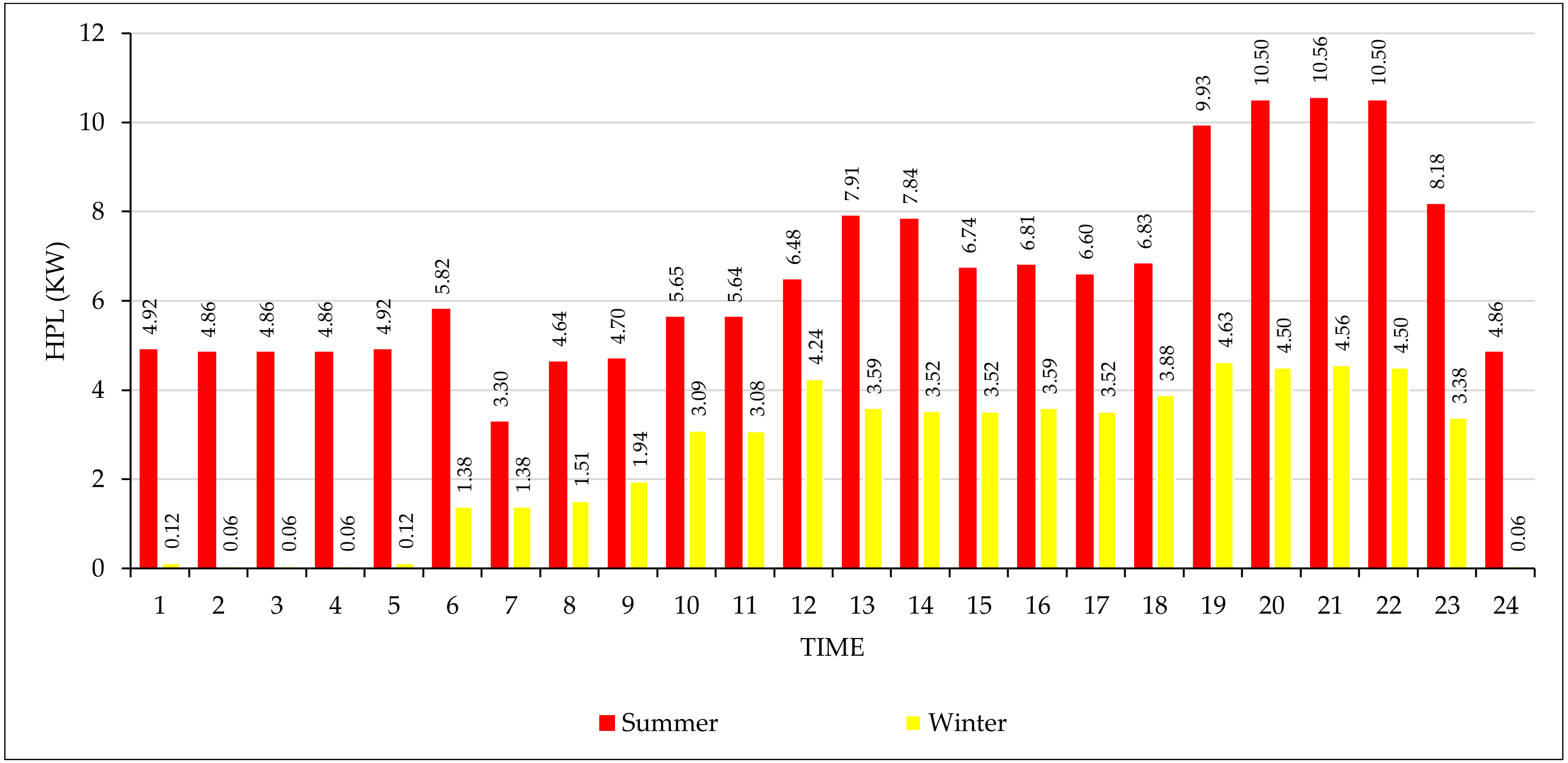

Fig 5.13: Seasonal variation based 24-hour load profile for High Priority Loads

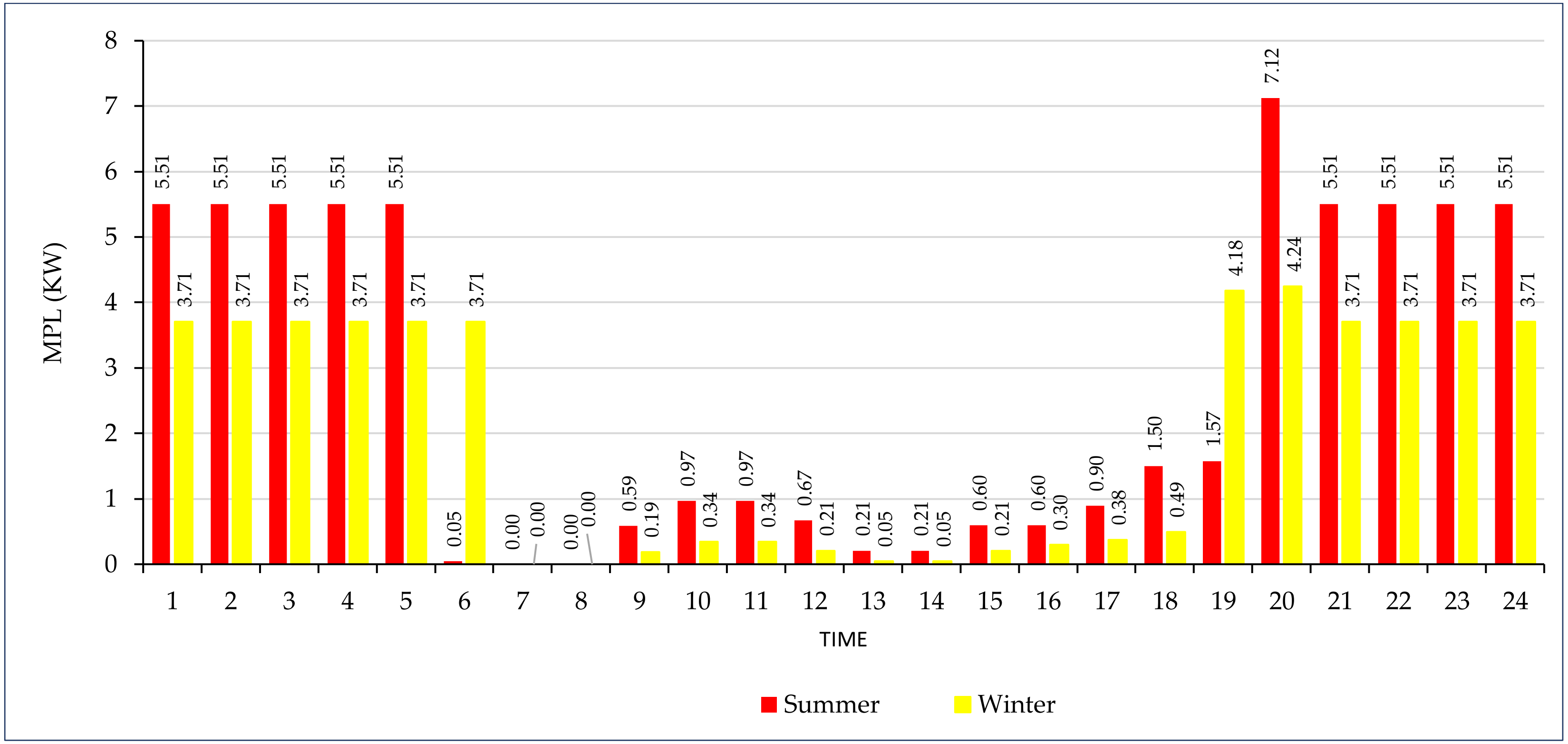

Fig 5.14: Seasonal variation based 24-hour load profile for Medium Priority Loads

5.7 TEA for various configurations of microgrid models

The step following the load profile improvisation was testing the various system configurations of the off-grid microgrid system. During this process, the off-grid systems were mainly classified into three main categories, with further sub-categorizations, based on placement /incorporation of the system parameters for meeting the required electrical load. The effect of the system configuration classifications was further examined on a prior basis of Economic Analysis (NPC and LCOE), and the Technical Analysis (Excess Energy (kWh/yr), Capacity Shortage (kWh/yr), and Unmet Load (kWh/yr)). The categorization of the system is as follow:

1. A complete DC power-based System Configuration
   - Hybrid System (PV+WT)
   - PV only
   - WT only
2. Deferrable Load (DL) connected to AC Bus bar
   - Hybrid System (WT connected to DC Bus Bar)
   - Hybrid System (WT connected to AC Bus Bar)
   - PV only
   - WT only
3. Deferrable Load (DL) connected to DC Bus bar
   - Hybrid System (WT connected to DC Bus Bar)
   - Hybrid System (WT connected to AC Bus Bar)
   - PV only

Table 5.12: Optimized TEA for various system configurations of remote microgrid

System Configuration Types		System Parameters				Economic Analysis (USD)		Technical Analysis (kWh/yr)			Autonomy (hr)
		PV	WT	BSU	Conv	NPC	LCOE	Excess Energy	Capacity Shortage	Unmet Load	
DC System Only	Hybrid System (PV+WT)	20	6	140	0	82325	0.19	37489	23.7	21	74
	PV only	41	0	172	0	110845	0.26	34875	33	32	91
	WT only	0	90	528	0	311202	0.73	558718	0.50	0.2	279
Deferrable Load to AC Bus	Hybrid System (WT connected to DC Bus)	22	5	144	12	90414	0.21	33370	31	29.5	76
	Hybrid System (WT connected to AC Bus)	22	4	152	12	89928	0.21	26971	30	32	80
	PV only	42	0	188	15	122335	0.29	34748	31	30	99
	WT only	0	65	592	15	277446	0.65	390795	18	18	313
Deferrable Load to DC Bus	Hybrid System (WT connected to DC Bus)	22	5	144	12	90414	0.21	33442	32	29	76
	Hybrid System (WT connected to AC Bus)	22	4	152	12	89927	0.22	26978	30	33	80
	PV only	43	0	184	15	122340	0.29	35695	33	33	97
	WT only	0	65	592	15	277441	0.65	390869	17	17	313

The classification was aimed at selecting an appropriate microgrid system configuration that was economically feasible and technically reliable. The focus was clean energy provisions to the remote community with uniform electricity access, aiming at a higher tier of electricity accessibility as per the Multi-tier Energy Access Framework of the ESAMP[14]. On the economic aspect, the primary focus was attaining a feasible NPC for the system on effectively accomplishing the technical aspects aforementioned, thus, promoting business models for attracting investors, state/central nodal agencies, and gaining the trust of community dwellers while ensuring their willingness to procure, use and pay for energy (electricity) services.

As seen in Table 5.12 above, from the first configuration, considering an off-grid system to be a simple DC-based system, which is futuristic for electricity provision, the system classifications were analyzed in three scenarios. The first scenario considered was a hybrid system (PV+WT) for electricity generation, followed by only PV and only WT. The results in the case of only PV and only WT indicated the systems to be economically implausible due to high NPC of the systems and technical unreliability as a result of higher capacity shortage. Also, the system assessment revealed higher excess energy generation but failed to meet the required load owing to the intermittency of the single-source systems. The "WT only" scenario

[14] https://www.esmap.org/node/55526

indicated substantial system autonomy with lower capacity shortage, but the TEA found the system unsuitable owing to excessive dependence on BSS. The over-dependence on BSS affects the overall cash flow of the system with higher replacement costs during the project lifetime. Although the assessment of the hybrid configuration results indicated, a lower NPC and LCOE selecting the case for pure DC systems was considered unfit for the remote scenario as the electrical appliances selected depend on AC and readily available for remote locations.

The other scenarios considered the DL connected to the AC and the DC Bus Bar in alternate for experimental purposes. Further classifications included a hybrid system (PV+WT), PV only, and WT only scenarios. Another contrasting result was obtained for the classifications, when the WT in the hybrid systems was alternately changed to the AC and the DC Bus Bar, owing to the higher effect of the wind energy penetrations on the grid compared to the solar energy penetration effect. Although the scope of the research was not intended to study the effect of renewable energy penetrations, the results indicated a little effect of altering the WT over the bus bars. The classifications for “PV only” and “WT only” systems were, however, found to be inappropriate due to the higher NPC and LCOE of the systems. Also, the large battery storage units, higher capacity shortage, and unmet load were an additional concern for such systems based on single-source renewable energy for electricity provisions.

Based on the assessments as tabulated in Table 5.12 above, the best selection for systems suitable for electricity access was the "Hybrid Systems with WT connected to AC" with either of the alternate options for connectivity of the DL load. However, with agricultural loads constituting Brushless DC (BLDC) motors gaining popularity in the site selected, a "DL connected to DC Bus Bar with Hybrid System (WT connected to AC) was considered as a preferable system to be implemented for electricity provisions for the desired loads. The selected system configuration for the provision of electrification access for the selected village of Sapra is, therefore, shown in Fig 5.15.

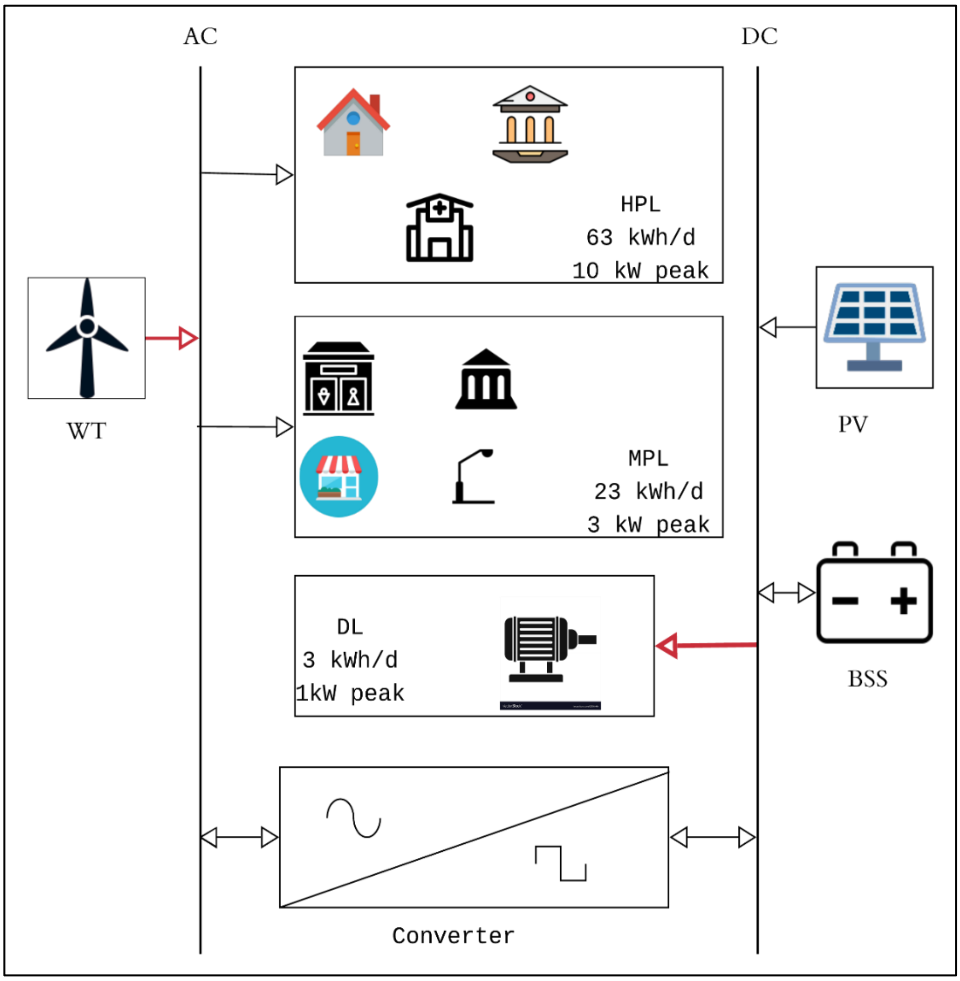

Fig 5.15: System architecture for HRES based on the developed Conceptual Framework

5.8 Improvements in Case 2 with CF over Case 1 with current practices

Table 5.13 below indicates a comparison of the two scenarios considered for validating the design improvements in the TEA based on the CF.

Table 5.13: Comparison of Scenario 1 vs Scenario 2 for remote microgrids

Hybrid Microgrid system	Economic Analysis (USD)		Technical Analysis (kWh/yr)			
	NPC	LCOE	Excess Energy	Capacity Shortage	Unmet Load	Autonomy (hr)
Scenario 1	355,734	0.42	158,249	65	46	34
Scenario 2	89,927	0.22	89,927	30	33	80

A quantitative analysis validates the improvements in the TEA design by incorporating the CF over the current practices for TEA, thereby, enabling scaling up of HRES for electricity provisions in the remote communities of the developing countries. From the assessment of the scenarios, it can be observed that the CF advocates improvements in the TEA design by incorporating a systematic energy management technique. From the research validation exercise, it can be observed that a pragmatic energy management approach in the form of the energy-efficient HRES system would contribute significantly towards the following purposes:

- Ensuring the accomplishment of efforts towards the indicator 7.1.1 of the SDG 7[15] for universal electricity access to the proportion of rural population currently experiencing the dearth of necessary energy access
- Ensuring tapping into the primary share of renewable energy sources for electricity generation, thereby reducing dependence on fossil fuels for meeting electricity requirements during peak loads.
- Judicious replacement of the appliances and managing the load profiles reduced the HRES system sizing, without compromising the essential electrical loads for holistic community development, which are positive steps towards achieving the various SDGs.
- A reduction in the system size (reduction in the number of components) yielded a feasible project establishment cost, thereby indicating a need in investments on energy-efficient approaches for infrastructures and technology for sustainable development services.

[15] https://sustainabledevelopment.un.org/sdg7

A further critical assessment of the TEA, where comparing the scenarios as tabulated in Table 5.13 indicates the significance of Scenario 2 of the case study, thereby validating the CF in the following ways:

- A reduction in the overall NPC of the system by a factor of 74 percent for achieving uniform electrification of the community rather than a hierarchical approach towards household electrification. If the current practice (Scenario 1) was to be followed, a microgrid needs a model to be designed considering a capacity shortage of 40-50 percent to match the NPC of a microgrid based on Scenario 2, in order to attract investors and nodal agencies for off-grid project investments.

- A reduction in the LCOE of the system by a factor of approximately 50 percent, ensures the willingness of the consumers to procure, pay, and use the off-grid systems for prolonged electricity services.

- An overall system autonomy of the system improved by a factor of approximately 55 percent, thereby, ensuring system reliability and resilience in events of technology failures or natural calamities.

- As a step towards attaining the indicators for energy-efficient systems for accomplishing SDG 7, the overall efficiency of the system improved by reducing the excess energy generation of the system by a factor of 80 percent.

5.9 Chapter Summary

This chapter validates the conceptual framework by effectively implementing a quantitative analysis for the research findings. The quantitative validation for the TEAs included a case study and featured two scenarios (with and without using the modules developed in the thesis). The comparison of the scenarios highlighted the significance of Scenario 2, which focusses on effective energy management, stakeholder involvement, and sustainability factors.

The key takeaways from the chapter indicate uniform electricity access for various loads in a rural village, which is necessary for the overall development of a rural community. Factors such as energy efficiency, system autonomy and a lower capital cost investment for off-grid electrification also highlighted as effective means of scaling up decentralized electrical systems for the remote communities.

The next chapter concludes the thesis and discusses the overall contribution of the research findings. Also, based on the premise of the present research in the thesis, the next chapter indicates future research activities that can be undertaken to improve the scenario of the remote electrification.

Chapter 6

Conclusions and Future Work

Chapter 5 has presented and validated the findings of this investigation. This chapter concludes the thesis by reflecting on the essential findings and making recommendations for future research to improve the design of remote off-grid microgrid systems, to provide better energy access in remote communities of developing nations.

Given the goal as mentioned earlier in the thesis, a detailed literature review was undertaken in order to understand the research trends to escalate electricity provisions for energy-dearth, remote communities (Chapter 1 section 1.1) The analysis highlighted the dominant focus on electricity access households only in the villages, neglecting a "unified electricity approach" for holistic community electrification. This shortfall paved the way for the overall research objective of the thesis (Chapter 1, section 1.2).

The thesis then undertook the characterization of the dimensions of rural electricity services for sustainable, reliable and affordable energy service. Furthermore, the foundation of the objective was aligned in accordance with the goals and core target areas of the SDG7 established by the UNDP. Also, the literature analysis indicated a significant interest in TEAs of decentralized energy systems. However, the literature surrounding the TEAs primarily focused on pursuing assessments to solve the electricity crisis in developing countries without a holistic approach towards energy systems. Much of the research either considered electrifying only the households, with a few using diesel gensets as energy sources and the rest using single-source renewable energy systems (typically PV) for means towards energy access. The non-uniformity in the approach, due to the absence of a standardized framework, reflects a negative impact on the scaling-up process of the off-grid systems and hinders the accomplishment of the SDG7. The need to improve the design approach of TEA in order to enhance the global rural electricity scenario, thus, paved the way for the primary objective of the thesis.

6.1 Research Analysis and Outcomes

The methodology adopted for developing the CF was the Technology and Policy Assessment (TPA) approach, developed by the UK Energy Research Centre (UKREC), which typically follows a combination of "qualitative and quantitative" research methods.

The initial outcome from the research analysis was the identification of the CAARLS attributes (Chapter 2, section 2.3). These attributes were extensively utilized in the thesis for evaluating the cases of underpinnings in the remote off-grid systems in the developing countries. The CAARLS assessment was undertaken as an integrative research approach, which proved to be vital as it was adopted in the body of the CF as "Module 2a", termed as "Retrospective Cohort Analysis" for investigating stalled microgrids for remote communities.

Another research outcome based on the analysis was the critical evaluation of the existing frameworks and toolkits for rural electrification (Chapter section 2.4). The investigation of the toolkits yielded substantial information for developing a comprehensive and reliable framework, adequate to address the techno-socio-economic dimensions that align exclusively with improving the design for TEA and the remote electrification processes aligned with the SDG7.

6.2 Achieved Research Objectives

Based on the research analysis, the primary research objective achieved in the thesis was establishing a "Conceptual Framework" to improve the design practices of microgrids with an emphasis on the TEA component (Chapter 3 section 3.3). The CF was developed based on a set of logical instructions for an epistemic approach to the design of sustainable remote off-grid systems in the developing countries. The CF mainly comprised four modules based on the convergence of attributes towards a sustainable remote microgrid for rural electrification. The process of verification and the validation of the CF were exclusively associated with the development of the CF, which further strengthened the accomplishment of the research objective.

6.2.1 Qualitative Research Outcomes

The modules constituting the CF were verified by involving a focus group constituting the experts from academics, sustainability consultants, renewable energy practitioners, industrial experts and chairs of IEEE working groups. The verification process comprised four stages and was critical in confirming the significance of the CF while featuring the essential needs for improving the remote electrification scenario (Chapter 4, section 4.2). The significant outcome of the verification process was the consideration of sustainability aspects of the renewable energy systems, thereby ensuring that the dimensions and the targets of the SDG 7 were fulfilled (Chapter 4 section 4.21.1.1, section 4.2. Specifically, the following is noted:

- Replacing the Diesel Gensets: Effective rural electrification master plans identified in the form of national rural electrification planning and policy assessments led to significant outcomes, resulting in the replacement of the diesel gensets in designing the remote microgrids for meeting the electrical loads, which is an action towards climate change (SDG 13). As a result, the transition to a sustainable energy future is accelerated towards meeting the SDG 7 (target 7.2), whose aim is to substantially increase the share of renewable energy in the global energy mix (Chapter 3 section 3.3.2.2)

- AOMR actions and indicators: In order to achieve the long-term viability of the energy systems, an in-depth social perspective was integrated into Module 1. The introduction of the AOMR actions and indicators was a critical aspect considered for bridging the gap between the project developers and the stakeholders by engaging the energy users in the system development process. The actions and the indicators feature duties and the responsibilities of the people associated with the project development phase and thereafter. Also, an indication of the behavioural aspects of the energy consumers towards the energy system is determined by the AOMR actions. Lastly, the AOMR actions and indicators delivered vital information about the project monitoring strategies and lay the foundation for overall transparent conduction of duties and responsibilities. The outcome of the research finding in the thesis is a vital step towards amending the global standard IEC/TS 62257-6, which further improves the design approach of the TEA. Moreover, with the various SDGs interlinked to the SDG7, the outcome of the AOMR is considered to escalate a holistic, sustainable development of the remote communities. (Chapter 3, section 3.3.1.2)

- Identification of the Rural Electrification Typology: Module 2 of the CF indicated a research outcome towards identifying a typology for the rural electrification. The research findings align with the improvement in the design approach of the TEA, which makes room for the reduction of the complexities of rural electrification by systematically classifying the remote microgrids based only on the renewable energy-based systems for an individual or collective electrical system. Besides, the dispatch strategies indicated the improvement in the system design approach for remote electrification. It can, therefore, be stated that along with improving the TEA design, the research outcome also speaks to the targets of the SDG7 (target 7.2 and 7.B), thereby enabling clean electricity access for rural communities (Chapter 3 section 3.3.2.1).

6.2.2 Quantitative Research Outcome

This section outlines the quantitative outcomes that constitute the validation process of the CF. The quantitative results, based on a quasi-experimental approach using an appropriate computational tool, indicated (potentially) significant improvements in the TEAs of remote microgrids.

An improvement in the electrical load profile design for the remote community is highlighted in segmenting the various community loads and prioritizing a holistic approach towards universal access to electricity, rather than a hierarchic system of electrifying the households (Chapter 5 section 5.5). The process of assessing the intended user's daily energy needs and the usage patterns based on the lifestyle of the specified community served as valuable information for improvements in designing the microgrid model for the TEA. The quantitative outcome validated Module 2 of the CF while aimed at achieving the target 7.1 of the SDG 7.

Furthermore, the validation outputs of Module 3 of the CF provided clear indications in the techno-economic evaluations of the remote microgrid. The outputs based on the simulation results indicated the possibility of achieving a sustainable, reliable, and feasible microgrid system for a remote community deficit of the necessary energy access - a significant outcome of an energy-efficient system directed towards proper energy management for the off-grid system. The outcome highlighted a substantial reduction in the average electrical load demand of the community and the overall system sizing. A reduction in the component sizing led to lowering the overall NPC, and the LCOE of the energy system without compromising the essential electrical needs. Also, the quantitative outcome improved the system autonomy, thereby enhancing the reliability aspects of the off-grid renewable-based energy systems.

Considering the research outcomes as discussed above, careful observation also reveals the convergence of the quantitative outputs in achieving the targets of the SDG 7, in addition to validating the CF. The following factors demonstrate the accomplishment of the targets for SDG 7:

Table 6.1: The research output directive towards the SDG 7 targets

Quantitative Research Outputs	SDG 7 Target Areas
Improved load profile design for uniform electricity access	Access to Energy (SDG 7.1)
100 percent renewable energy-based system meeting the electrical load demands	Renewable Energy (SDG 7.2)
Improved Energy Efficiency and Energy Management of the system	Energy Efficiency (SDG 7.3)
Reduced NPC and LCOE	SDG 7. A
Improved System Autonomy and overall system reliability	SDG 7. B

6.3 Theoretical Contribution of the Research

The accomplishment of the objective of the thesis in developing the Conceptual Framework enables uniformity in electricity access and improves the design process of microgrids in developing countries, thereby contributing significantly to the body of knowledge.

The research provides essential information about the renewable energy-based microgrid design and planning indices, such as the uniform access to electricity, designing the users' energy needs, and their corresponding load patterns. Also, by integrating energy-efficient approaches, the research has effectively contributed towards designing a well-managed decentralized system having a further implication on the overall system autonomy. As investment is a vital factor responsible for the success of the Sustainable Energy for All (SEforALL) projects, the feasibility aspect of the hybrid renewable energy system can provide guidelines to procure capital investments for electricity development projects in remote communities. The proposed Conceptual Framework highlights significant features involving stakeholder engagements for the project developments and indicators focussing on the responsibilities and behavioural aspects of the energy provider and the users for prolonged electricity services.

6.4 Practical Contribution of the Research

The thesis has demonstrated amendments in the global standard for rural electrification IEC/TS 62257-4, which reveals very considerable practical applications. As it were, the research contributions provide a reference point for researchers, designers, planners, policymakers and other stakeholders of interest in conceptualizing and proceeding with the TEAs and developments of hybrid renewable energy-based electrification systems for remote communities.

In addition to the theoretical contribution, the thesis provides significant practical contributions for electrifying remote communities in developing countries through hybrid renewable energy systems (without using fossil fuel as an energy source). In addition to usage of the renewable energy source for energy access, the research highlights the provision of uniform access of the electricity through different loads, which are considered essential. It has the potential to improve the overall social well-being of the people in rural communities. By improving the design approach for rural off-grid microgrid systems, the thesis has identified the dimensions of the Sustainable Developing Goal 7 for "affordable, reliable, sustainable and modern energy for all," and its impact on the other SDGs enabling directions towards the target 2030 of the United Nations.

6.5 Recommendations for Future Research

Several topics presented themselves as potential scope to further the present work and advance knowledge in electrifying remote communities while scaling the goals towards the targets for SDG 7. In view of this, the following research activities are recommended as future investigations:

- Development of the Conceptual Framework into a Pre-feasibility Toolkit- The present thesis established a Conceptual Framework and determined the process flow for the modules in the framework. However, further development of the framework into a toolkit using appropriate software applications would help in determining the pre-feasibility of an off-grid energy system in the context of developing communities. The software toolkit comprising the modules of the CF can enhance the capacity of the communities, with limited/no skills and knowledge in sustainable energy electrification, to produce an initial set of ideas to support microgrid investments and escalate the deployments. A pre-feasibility software tool based on the CF developed in this research is on a development phase where the alpha-testing has been achieved. The development of the software model is undertaken by the IEEE SESDC taskforce committee aiming to develop the software by early 2021 fully. The preceding steps and the beta-testing of the software will be discussed at the annual taskforce committee meeting at the annual IEE Power Engineering Society (PES) General Meeting 2020. Since an early disclosure of the features in the software model cannot be disclosed due to confidentiality issues, snapshots of the alpha-tests have been presented in Appendix IV.

- Practical Implementation: The next practical and logical step for the advancement of the present research would see a practical implementation of the microgrid based on the newly developed CF, which improves the design of TEAs. The stride towards practical implementation would highlight a real-world scenario, featuring the issues not encountered during the simulated scenario; an example is the effect of distances between the electrical loads on the overall electricity losses, the lifetime, and the average annual throughput of the storage units. To this end, the CF model is now practically tested for implementation with some additional features as necessary for industrial applications in New Zealand. The implemented model will be used by a power utility firm to analyse the emerging distributed energy resources and industrial projects in New Zealand.

- Financial Assessment: On the practical implementation of the energy system, a detailed financial and life cycle assessment of the energy system would ensure the feasibility of the system. Also, it would provide practical budgeting experience for future capacity extensions of the microgrids.

- Refining the Definition of Microgrid: There is a need to refine the paradigm of a microgrid, concerning the long-existing definition proposed by US DOE, to be more inclusive of the societal needs that dynamically change over time, thereby ensuring the resilience and sustainability of the overall system.

- Rethinking and reclassifying the Multi-tier Energy Framework: Presently, the assessment for measuring energy access is based on the Multi-tier Framework developed by the ESAMP, under the SEforALL. Underlying the framework is the MTF assessment approach, where the indicators for electricity access is evaluated based on tiers (Tier 0 is the lowest, and Tier 5 is the highest). However, the tier levels indicated in the MTF is a generalized classification technique used for energy assessments for both the urban and rural electricity scenario creates ambiguity in terms of the assessments for energy access. The complexity in the assessment can be resolved by developing separate frameworks for the different scenarios based on the electricity demands and the appliances usage patterns.

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Appendix I

- Renewable Purchase Obligations- Mandatory regulations for the state/provincial electricity agencies to generate/purchase/sell a certain percentage of renewable energy, which in return can spur the developments of decentralized electricity systems in the rural communities. With the urban areas already facilitated by the centralized grids, and the obligation of commitment for the state agencies to the RPOs, a shift in interest towards investments/installations of decentralized systems in rural areas can provide opportunities to create demand for renewable energy throughout the country. This process can thereby generate excitement for the central agencies to amend the electrification policies creating new opportunities for off-grid microgrid projects.

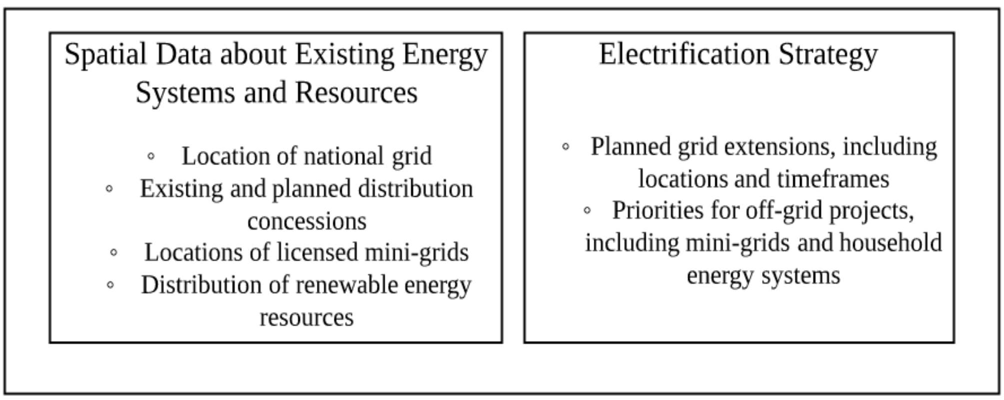
- Renewable Energy Policy and Rural Electrification Policy- A country's energy policy, or rural electrification policy, established the government's goal for universal energy access, including specific targets and planned activities to meet those goals. The procedure typically precedes an energy law or rural electricity act that establishes an institutional and legal framework. In many cases, the energy policy identifies new requirements needed to achieve energy access goals. In other instances, subordinate legislation such as regulations, rules, and bylaws, provides enough support for governments to begin implementing the policy.

Energy policy can do more than lay the groundwork for future legislation. The plan can establish universal energy access goals and prioritize microgrid solutions as a pathway to achieving those goals. A country's energy policy is often the first official document to signal a change in direction and pave the way for the private sectors to provide electrical solutions to rural communities.

- Rural Electrification Strategy- A rural electrification strategy can lay out a plan of action to achieve the set national energy policy. Government policies can combine the energy policy and rural electrification strategy into a single document to accomplish the task for energy access in remote communities.

- Rural Electrification Master Plan-A rural electrification master plan establishes directions for the government in achieving energy access goals and targets as following the energy policy drafted. The master plan can provide a roadmap to attain specific goals and objectives, often over a remote microgrid project timeframe (20-25 years). The timeline should demonstrate how proposed activities will achieve the universal access targets established in the energy policy by integrating various approaches to enhancing energy access, developing where the government will extend the grid and determining where it will support off-grid electrification.

From experience, it is often observed that the Governments, however, hesitates to specify the regions not to be accessed by centralized grids in its national electrification plans. To build local support for off-grid systems, governments can thereby educate communities about the high-quality energy services they can potentially provide and generate options for independent electricity providers and donors to engage in the electrification plans actively. Donors can play a crucial role in helping governments integrate microgrids into their national energy strategies. In particular, donors can help governments prepare the rural electrification master plan and a regulatory framework for region-specific microgrid policies and project establishments. The critical components of a remote electricity master plan shown below.



Critical Components of a Rural Electrification Plan

- Replacing diesel gensets- Using renewable energy to offset diesel fuel consumption can be a cost-effective, environmentally friendly strategy for microgrids. Displacing diesel often reduces costs, and cost savings are likely to increase in years to come for an off-grid in terms of payback for renewable energy projects. The cost of renewable energy technologies, particularly solar panels, have decreased substantially over the last decade. At the same time, the price of diesel fuel, which is persistently volatile, is increasing. Despite the economic advantages of renewables, energy providers continue to operate diesel-only off-grid systems for a variety of reasons. These factors include long-term use of and experience with diesel technology, lower upfront capital costs compared with renewables, lack of information on how to integrate renewable energy technologies into existing diesel systems, and lack of guidelines in the international standards for technical specifications, related to replacing gensets with clean energy fuel sources.

- Electricity Act or Energy Law- An electricity act, or energy law, establishes the legal and institutional framework for rural electrification in general and decentralized electricity systems in particular, usually through an act of parliament or congress. An electricity act outlining the key factors and responsibilities in facilitating and regulating the generation, transmission, distribution, supply, and tariffs for rural electrification can benefit business mechanisms to function and flourish in the rural sectors. These laws can also direct the specific electrical agencies to prepare additional plans and strategies as needed in cases of catastrophic calamities, thereby, adding resiliency features to boost up the overall system reliability and trust of the consumers.

Policies for supportive investment for remote microgrids- In many countries, laws either prohibit or fail to address private-sector distribution and sale of electricity to the villages. Without a clear legal basis to operate microgrids, developers cannot secure licenses to generate and distribute power. Without permits, private investors have no legal protection in case of dispute, and they often cannot apply for loans. While investors may still develop projects in this unclear context, they will choose smaller and less-efficient investments with weaker economies of scale. More explicit regulatory frameworks provide developers with the confidence to think big, and in the energy sector, more significant projects produce better economic returns. To mitigate risk, project developers may install second-hand diesel generators and temporary distribution networks that they can quickly sell or move. Legalizing privately operated mini-grids can spur additional public investment along with private-sector investment.

- Tariff Regulations- Remote microgrids can be financially sustainable if project developers can set tariffs that reflect costs. When the government requires private operators to set tariffs too low, investors cannot recover their losses. A persistent challenge is that consumers and local leaders in remote communities often expect to pay the same tariff as customers served by the national/centralized grid in urban areas with unreliable energy services and quality. The interest of the consumers in the rural scenario paying higher tariffs are based on the confirmation of the service quality of the microgrids and understanding the benefits of the electricity procurements for improving the quality of life. Also, requirements arise for the governments create tariff policies that can sustainably weigh fairness for customers against the value of private sector investment. Thereby, the government can subsidize tariffs for rural power by providing grants and concessionary loans to private developers and communities.

- Transparent Grid Expansion- Tariff flexibility alone is not enough to attract large-scale private-sector investment in mini-grids. Developers also need access to the country's plan for expanding the national grid to specific areas within a specified timeframe. Transparent grid expansion plans give project developers the confidence to invest in mini-grids in the regions that won't be served by the national network. Without transparency, developers run the risk of building mini-grids in areas scheduled for grid expansion, thereby losing their investments.

Another vital aspect for transparent grid expansion plans lies in increasing the consumers' willingness to pay higher tariffs. This is due to the fact owing to the realization by the remote communities of not gaining centralized grid access for a specified timeframe. As such, transparent communication of the governmental plans and activities with dwellers in rural areas about chances and alternatives to electricity services are apt procedures to initiate community interests for participatory involvements with the private energy developers and service providers to gain energy access. It can also aid in ensuring the willingness to electricity access from off-grid systems supply systems having equivalent to service qualities to the centralized grid-based power services.

Appendix II

SES DC WG Meeting – 12 April 2019

Attendees:
Dr Joseph Mutale
Brucoli, Maria
Abhi Chatterjee
Stephen Cook
Peter Dauenhauer
Robert Nutter
Kostas Latoufis
Yke Wynia
Barry Rawn
Damien Frame
Daniel Adegbie
Peter.Alstone
Tom Callsen
Joe Stansbery
Michael Warner

Notes:

- We reviewed Abhi's Conceptual Framework Design for Remote Microgrids for Rural Communities. BIG thanks to Abhi for all of his hard work pulling this together. The framework and a briefing packet about it are attached to the E-mail. Please look it over and provide comments to Abhi, cc: Peter and myself.
- In general, the framework seems very comprehensive. It looks to cover most all of the points that someone would want to touch on when assessing a remote microgrid project.
    - BUT: That was the assessment of fifteen experts. More input from different perspectives is needed!
- The Basic Planning Framework (page 1 of the Concept map) brings up most of the areas that the Toolkit will need to cover.
- One gap in the framework that needs to be addressed is that there doesn't seem to be a strong enough focus on sustainability, especially with respect to environmental impacts and benefits of these types of project.
    - The Basic Planning Framework includes assessments for Energy Poverty, Benefits, and Resources. Energy Poverty definitely addresses one important sustainability factor. While Benefits and Resources can be interpreted to include environmental factors, it is important to put much more emphasis into this area. Robert's recommendation is that in this construct, a marker for Environmental Assessment be included

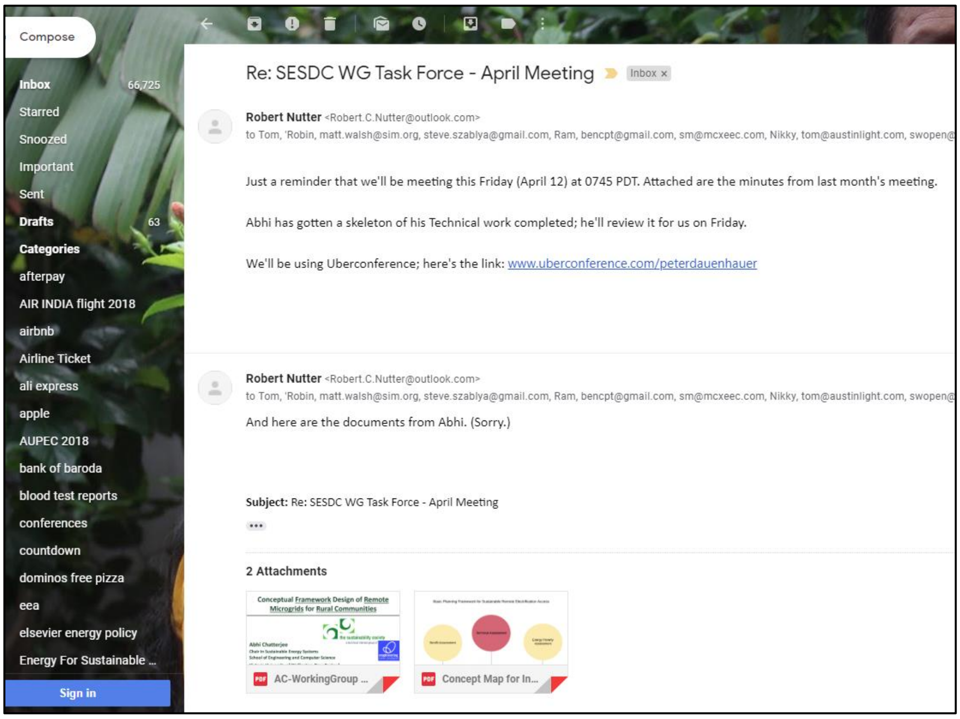
    - Other sustainability factors that are examined include the willingness to pay (financial sustainability) and the need to hire local residents to operate and maintain the system (social sustainability).
- The complexity of the framework was discussed. All of the issues it identifies absolutely must be addressed at some stage during project development. But the tool as currently laid out may prove to be a bit too complex for the average or intended user.
    - It's recommended that Abhi works on each of the points listed in the five modules and see if there are ways to simplify them, or if there is a way to gather and provide information. Abhi will draft a few sentences for each of the bullet points that further explains his intent and approach; which will then review these provide a summary at the June telecon.

The next meeting will be Friday, May 3 at 10:15 AM EST.

Goals

- Suggestions:
    - Beta testing of Financial Toolkit
    - Socio-Economic Toolkit: Build skeleton
    - Demand calculation/Analysis Toolkit: Build Skeleton
    - Summary of Why Toolkit is Important and Relevant
        - How and why is ours better?

➢ ***Ready to present and discuss in Montreal!***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conferences
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Sign in
Re: SESDC WG Task Force - April Meeting
Inbox ×
Robert Nutter <Robert.C.Nutter@outlook.com>
to Tom, 'Robin, matt.walsh@sim.org, steve.szablya@gmail.com, Ram, bencpt@gmail.com, sm@mcxeec.com, Nikky, tom@austinlight.com, swopen@
Just a reminder that we'll be meeting this Friday (April 12) at 0745 PDT. Attached are the minutes from last month's meeting.
Abhi has gotten a skeleton of his Technical work completed; he'll review it for us on Friday.
We'll be using Uberconference; here's the link: www.uberconference.com/peterdauenhauer
Robert Nutter <Robert.C.Nutter@outlook.com>
to Tom, 'Robin, matt.walsh@sim.org, steve.szablya@gmail.com, Ram, bencpt@gmail.com, sm@mcxeec.com, Nikky, tom@austinlight.com, swopen@
And here are the documents from Abhi. (Sorry.)
Subject: Re: SESDC WG Task Force - April Meeting
2 Attachments
Conceptual Framework Design of Remote Microgrids for Rural Communities
Abhi Chatterjee
AC-WorkingGroup ...
Concept Map for In...

SES DC WG Meeting – 14 September 2018

Attendees:
Abhi Chatterjee
Robert Nutter
Jaspreet Singh
Peter Dauenhauer
Joe Stansbery
Amal Mallavarapu Aran Eales
Stephen Cook
Nirupama Kumar
Brucoli Maria

Notes:

- The bulk of the meeting focused on Abhi's work on microgrids, and his approach to determining loads, and discussing operational challenges of remote microgrids.
- Abhi identified a significant challenge of remote microgrids: while there is lots of effort put into design and installation of such projects, there is nowhere near the same level of attention paid to operation and maintenance. As a result, such projects tend to fail after a few years, which can be discouraging not only to the community, but also to other communities considering and investors such projects.
- Abhi is looking into this area as part of his PhD research, and is looking to delineate the reasons for failures of remote power projects and develop a framework.
    - One such reason identified is the inability of the project to expand to accommodate load growth. Typically, designers will assess a village's existing loads, and not always by the most rigorous means (e.g., they'll count light bulbs). They then go back to their offices, design a solution, and bring it in to install it. There tends to be little accommodation for the increase in load or consumption once a village is electrified.

- Robert asked Abhi to expand on his paper and look at framing it in terms of performance risk. The intent is to use his work to form part of the Toolkit, specifically the sections regarding Technical Risk. The group briefly discussed one way to approach risk management, by looking at Probability and Consequence. I.E., what are the odds that something will fail, and what will happen if the failure occurs?
- The group discussed the potential to use the World Bank's Multi-Tier Framework (MTF) to establish general levels of electrical service and loads. However, the MTF is geared toward households; it does not seem to address village-scale loads, which would seem to be where a lot of load growth could come from. Abhi stated that the MTF may not be the best guidance, that an on-site survey is still the best method.

- In his research, Abhi has looked at most typical village loads (all but cottage industries). By using the most energy efficient items (light bulbs, appliances, VFD motors and the like), the peak loads required of a rural microgrid can be reduced enough so that the capital costs of such a system can be reduced by around 40%.
- It seems that his work can lead toward development of a reasonable baseline / template to determine the electrical loads for a generic off-grid community, followed up by an on-site assessment working with local stakeholders to refine the model.
- Abhi discussed this in terms of his current research, especially in terms of the failures of recent systems. He is looking for case studies to use as bases for his modelling.

Action Items:

- Abhi will work on reframing his terms of risk factors, as part of the Risk Management section of the Toolkit.
- Abhi will continue looking into developing the tools for predicting village loads.

The next meeting will be Friday, October 5 at 10:15 AM.

From: Robert Nutter

Sent: Wednesday, May 30, 2018 5:00 PM

To: Tom Callsen; 'Robin Podmore' (robin@incsys.com); matt.walsh@sim.org; steve.szablya@gmail.com; Ram Ramachandran; bencpt@gmail.com; sm@mcxeec.com; Nikky Avila; tom@austinlight.com; swopen@seattleu.edu; paras@ghe.co.in; jmgunawa@srpnet.com; beckshirley@gmail.com; gjimenez@cec.uchile.cl; donald.brooks@cpuc.ca.gov; vera.silva@edf.fr; ana.manzanares@comed.com; nathanjohnson@asu.edu; kathryn.a.mullin@gmail.com; khr003@connections.mcdaniel.edu; morrise3@seattleu.edu; d.gersh@berkeley.edu; noahkittner@gmail.com; laura.garga@gmail.com; wlee@uta.edu; peter.alstone@gmail.com; rjain5@ncsu.edu; thomas.callsen@ieee.org; Paul.Savage@nextekpower.com; miguel.lopez-botet-zulueta@edf.fr; krahn@energyscienceinternational.com; aadepoju@firstoptiontech.com; daniel.kammen@gmail.com; Seth Myers (sethmyers@att.net); rsabzehgar@mail.sdsu.edu; pena.ivonne@gmail.com; femtouchng@gmail.com; jmomoh@howard.edu; Daniel Adegbie; deepak.rajagopal@gmail.com; gunjan.link@gmail.com; chris.dent@durham.ac.uk; jquintero@uao.edu.co; Jose Daniel Lara Aguilar; pfribeiro@ieee.org; ms@iit.edu; kfdunn@gmail.com; baiblyden@gmail.com; rhalmeida@fc.ul.pt; kammen@berkeley.edu; Larsen, Ray (larsen@slac.stanford.edu); sankar.vu@gmail.com; josvandenakker@gmail.com; m.m.wilson@ieee.org; Mowry, Greg S.; earlschmid@desertpowerinc.com; rolosrevenge@gmail.com; rodpalma@cec.uchile.cl; kyriako.a@gmail.com; ravi.seethapathy@gmail.com; aelandaloussi@burnsmcd.com; Durreh Tabassum; Amal.Mallavarapu@cgglobal.com; rsims@smartergridsolutions.com; joe.stansbery@windlogics.com; amal.mallavarapu.r@ieee.org; Aran Eales; aran.eales@btinternet.com; Stephen Cook; jaspreet.singh@arup.com; Abhi.Chatterjee@ecs.vuw.ac.nz

Cc: Niru Yahoo (nirupama.pkumar@yahoo.com); Brucoli, Maria; Henry Louie; Dr Joseph Mutale; peter.dauenhauer@gmail.com

Subject: Re: SESDC WG Task Force - May Meeting

And here it is with Stephen's last name. (Sorry!)

From: Robert Nutter

Sent: Wednesday, May 30, 2018 4:30 PM

To: Tom Callsen; 'Robin Podmore' (robin@incsys.com); matt.walsh@sim.org; steve.szablya@gmail.com; Ram Ramachandran; bencpt@gmail.com; sm@mcxeec.com; Nikky Avila; tom@austinlight.com; swopen@seattleu.edu; paras@ghe.co.in; jmgunawa@srpnet.com; beckshirley@gmail.com; gjimenez@cec.uchile.cl; donald.brooks@cpuc.ca.gov; vera.silva@edf.fr; ana.manzanares@comed.com; nathanjohnson@asu.edu; kathryn.a.mullin@gmail.com; khr003@connections.mcdaniel.edu; morrise3@seattleu.edu; d.gersh@berkeley.edu; noahkittner@gmail.com; laura.garga@gmail.com; wlee@uta.edu; peter.alstone@gmail.com; rjain5@ncsu.edu; thomas.callsen@ieee.org; Paul.Savage@nextekpower.com; miguel.lopez-botet-zulueta@edf.fr; krahn@energyscienceinternational.com; aadepoju@firstoptiontech.com; daniel.kammen@gmail.com; Seth Myers (sethmyers@att.net); rsabzehgar@mail.sdsu.edu; pena.ivonne@gmail.com; femtouchng@gmail.com; jmomoh@howard.edu; Daniel Adegbie; deepak.rajagopal@gmail.com; gunjan.link@gmail.com; chris.dent@durham.ac.uk; jquintero@uao.edu.co; Jose Daniel Lara Aguilar; pfribeiro@ieee.org; ms@iit.edu; kfdunn@gmail.com; baiblyden@gmail.com; rhalmeida@fc.ul.pt; kammen@berkeley.edu; Larsen, Ray (larsen@slac.stanford.edu); sankar.vu@gmail.com; josvandenakker@gmail.com; m.m.wilson@ieee.org; Mowry, Greg S.; earlschmid@desertpowerinc.com; rolosrevenge@gmail.com; rodpalma@cec.uchile.cl; kyriako.a@gmail.com; ravi.seethapathy@gmail.com; aelandaloussi@burnsmcd.com; Durreh Tabassum; Amal.Mallavarapu@cgglobal.com; rsims@smartergridsolutions.com; joe.stansbery@windlogics.com; amal.mallavarapu.r@ieee.org; Aran Eales; aran.eales@btinternet.com; Stephen Cook; jaspreet.singh@arup.com; Abhi.Chatterjee@ecs.vuw.ac.nz

Cc: Niru Yahoo (nirupama.pkumar@yahoo.com); Brucoli, Maria; Henry Louie; Dr Joseph Mutale; peter.dauenhauer@gmail.com

Subject: Re: SESDC WG Task Force - May Meeting

All, Here are the minutes from the meeting on May 18. Thanks again to those who participated, and to all of you for wanting to take part. Please read these over, send me any corrections, and look at the action items.

Appendix III

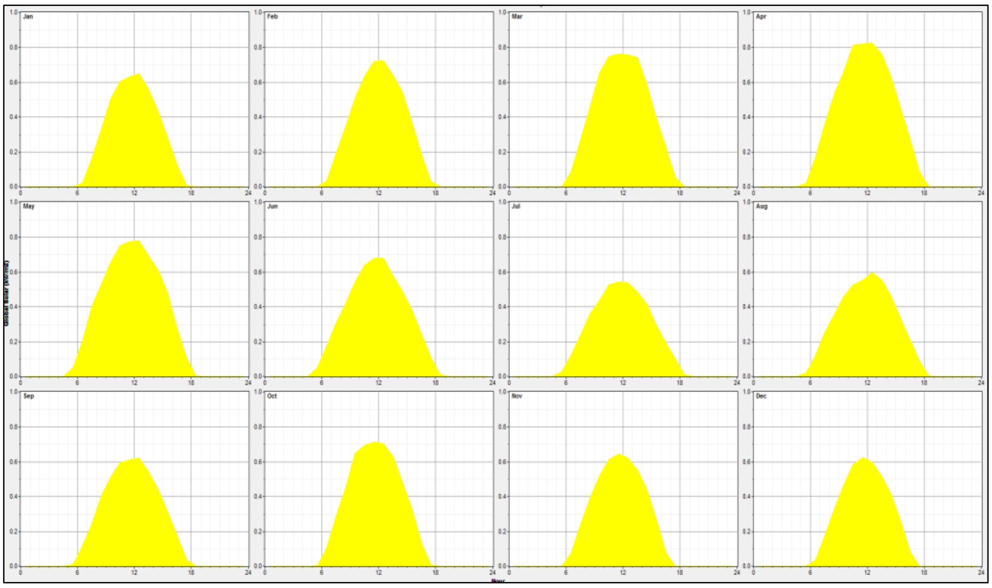


Figure 1. Monthly solar resource assessment for the selected location

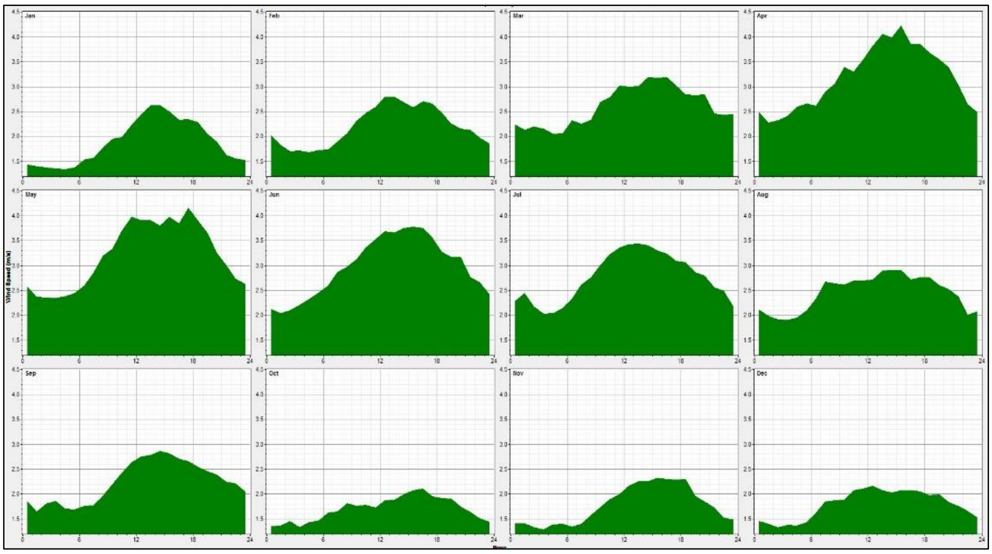


Figure 2. Monthly wind resource assessment for the selected location

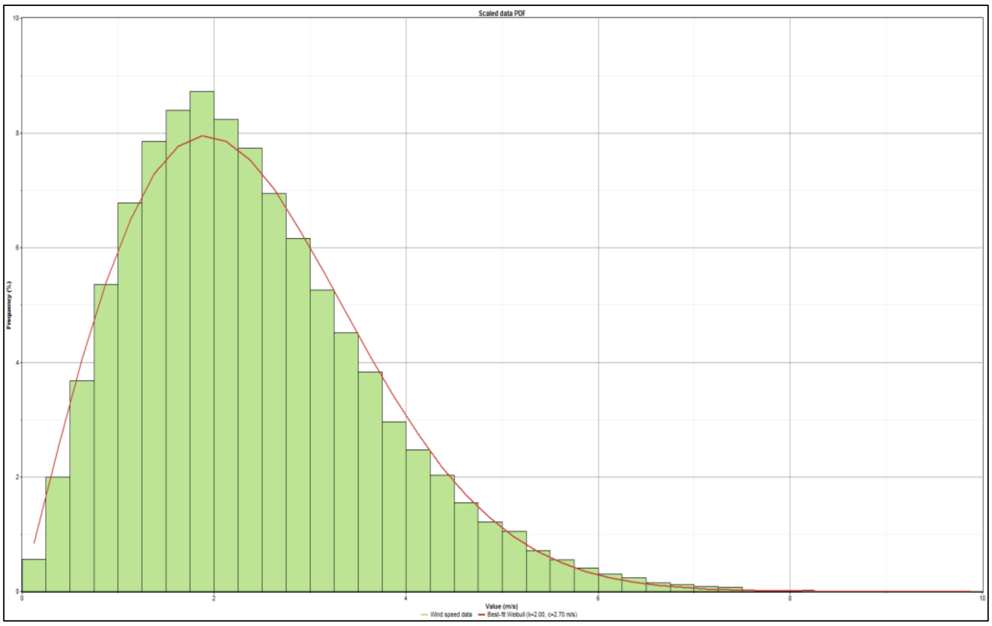


Figure 3.Wind diurnal pattern for the selected location

Table 1. Details of PV module inputs for simulation purpose

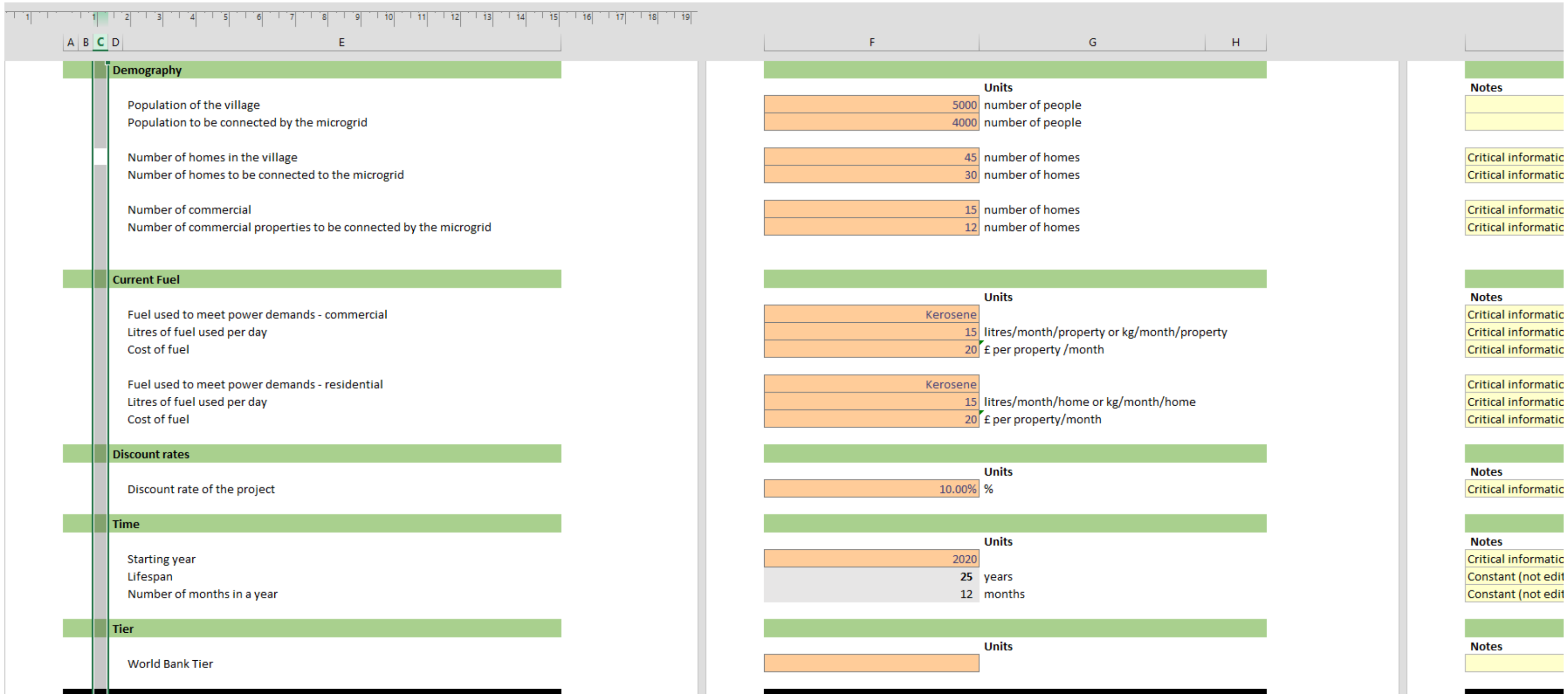
Derating Factor (%)	90
Lifetime (years)	25
Slope (degrees)	22.7
Ground Reflectance (%)	20
Maximum Power Point Tracking (MPPT)	N/A
Temperature coefficient of power (%/˚C)	-0.5
Nominal operating cell temperature (˚C)	47
Efficiency at standard test condition (%)	13
Rated Capacity (kW)	30

Table 2. Representation of surface roughness length for wind profile calculations

Terrain Description	Z_o (m)
Very smooth, ice or mud	0.00001
Calm open sea	0.0002
Blown sea	0.0005
Snow surface	0.003
Lawn grass	0.008
Rough pasture	0.010
Fallow field	0.03
Crops	0.05
Few trees	0.10
Many trees, few buildings	0.25
Forest and woodlands	0.5
Suburbs	1.5
City centre, tall buildings	3.0

Appendix IV

Snapshots of the pre-feasibility tool in its developing stage created is based on the CF presented in the thesis.



Demography		**Units**	**Notes**
Population of the village	5000	number of people	
Population to be connected by the microgrid	4000	number of people	
Number of homes in the village	45	number of homes	Critical informatic
Number of homes to be connected to the microgrid	30	number of homes	Critical informatic
Number of commercial	15	number of homes	Critical informatic
Number of commercial properties to be connected by the microgrid	12	number of homes	Critical informatic
Current Fuel		**Units**	**Notes**
Fuel used to meet power demands - commercial	Kerosene		Critical informatic
Litres of fuel used per day	15	litres/month/property or kg/month/property	Critical informatic
Cost of fuel	20	£ per property /month	Critical informatic
Fuel used to meet power demands - residential	Kerosene		Critical informatic
Litres of fuel used per day	15	litres/month/home or kg/month/home	Critical informatic
Cost of fuel	20	£ per property/month	Critical informatic
Discount rates		**Units**	**Notes**
Discount rate of the project	10.00%	%	Critical informatic
Time		**Units**	**Notes**
Starting year	2020		Critical informatic
Lifespan	25	years	Constant (not edit
Number of months in a year	12	months	Constant (not edit
Tier		**Units**	**Notes**
World Bank Tier			

Demography			
		Units	**Notes**
Population of the village	5000	number of people	
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Number of homes in the village	45	number of homes	Critical informatic
Number of homes to be connected to the microgrid	30	number of homes	Critical informatic
Number of commercial	15	number of homes	Critical informatic
Number of commercial properties to be connected by the microgrid	12	number of homes	Critical informatic
Current Fuel			
		Units	**Notes**
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Discount rates			
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Discount rate of the project	10.00%	%	Critical informatic
Time			
		Units	**Notes**
Starting year	2020		Critical informatic
Lifespan	25	years	Constant (not edit
Number of months in a year	12	months	Constant (not edit
Tier			
		Units	**Notes**
World Bank Tier			

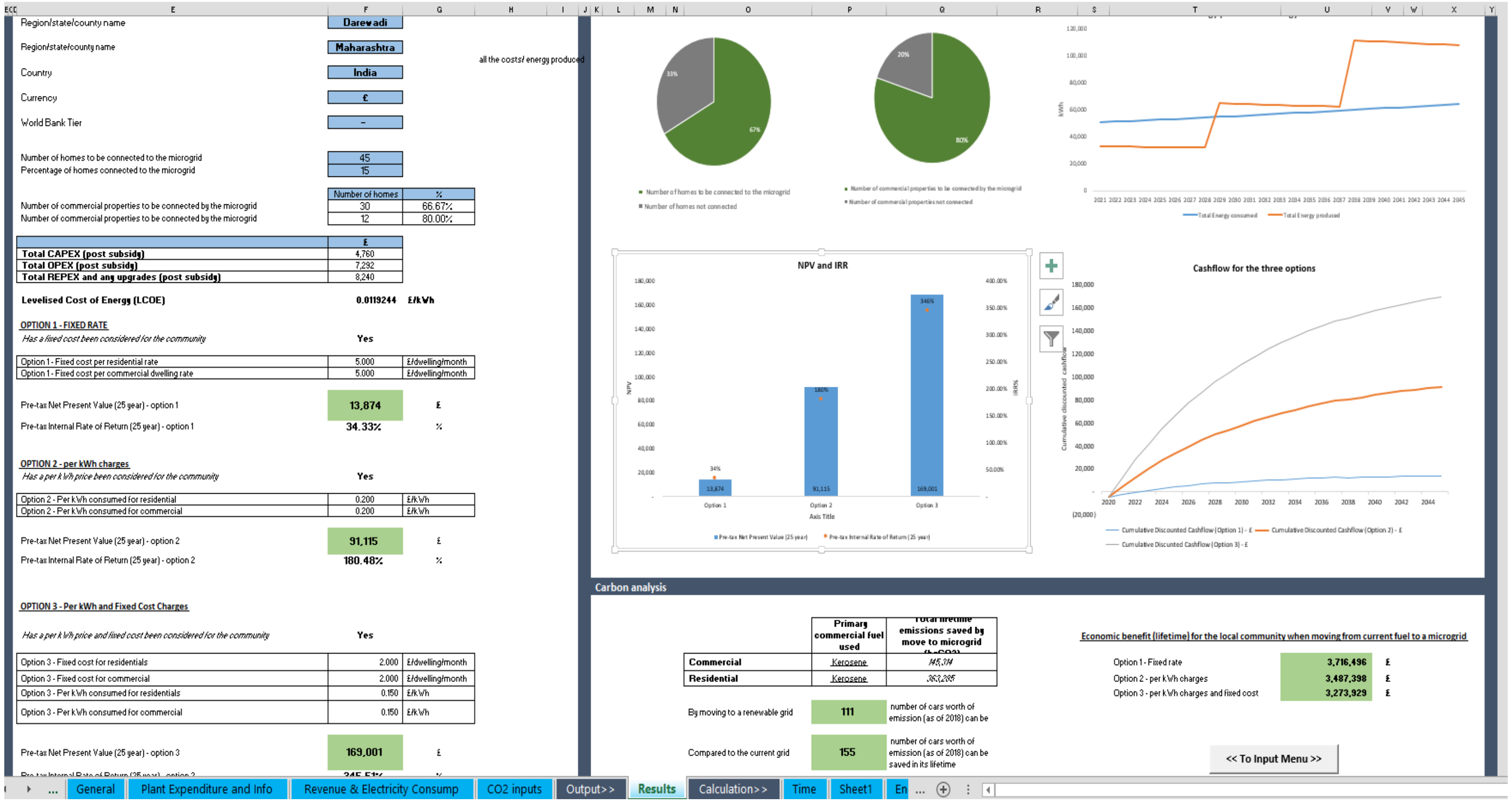
E	F	G	H	I
Batteries	1000	£		Critical information. Please ensure the right information is entered.
Inverters	800	£		Critical information. Please ensure the right information is entered.
Cost of a control setup	200	£		Critical information. Please ensure the right information is entered.
Transportation and last mile costs	200	£		Critical information. Please ensure the right information is entered.
Construction and surveys + other upfront project development costs	1000	£		Critical information. Please ensure the right information is entered.
Ancillary costs (such as for bulbs, fans, etc.)	1000	£		Critical information. Please ensure the right information is entered.

Operational Expenditure

		Units	Notes
Yearly total operational expenditure	200	£/year	Critical information. Please ensure the right information is entered.
O&M Escalator (%)	3.00%	%	Critical information. Please ensure the right information is entered.

Replacement Ependiture

Aditional plant growth CAPEX		Units	Notes
Number of growth phases for the microgrid plant	2		Critical information. Please ensure the right information is entered. It is advised to have growth phases linked to battery life (limited to 2).
Year of first growth phase	2029		Critical information. Please ensure the right information is entered. Please enter the year of the battery replacement if there are no growth phases. Please enter a year below the end of plant life year.
Year of second growth phase	2038		Critical information. Please ensure the right information is entered. Please enter the year of the battery replacement if there are no growth phases. Please enter a year below the end of plant life year.
First phase			
First phase plant size added	20	kWp	Please enter zero if there are no growth phases
First phase total expenditure - excluding batteries	2000	£	Critical information. Please ensure the right information is entered. Please enter zero if there are no growth phases.
First phase - Projected size of batteries added to the replacement	50	kWh	Please enter zero if there are no growth phases
First phase - Projected cost of batteries when first replaced	1000	£	Critical information. Please ensure the right information is entered. Please enter a value that suggests the batteries replacement cost and the upgr
Second phase			
Second phase plant size added	30	kWp	Please enter zero if there are no growth phases
Second phase total expenditure - excluding batteries	1300	£	Critical information. Please ensure the right information is entered. Please enter zero if there are no growth phases.
Second phase - Projected size of batteries added to the replacement	30	kWh	Please enter zero if there are no growth phases
Second phase - Projected cost of batteries when replaced the second time	6000	£	Critical information. Please ensure the right information is entered. Please enter a value that suggests the batteries replacement cost and the upgr



	F	G
Region/state/county name	Darewadi	
Region/state/county name	Maharashtra	
Country	India	
Currency	£	
World Bank Tier	-	
Number of homes to be connected to the microgrid	45	
Percentage of homes connected to the microgrid	15	

all the costs/ energy produced

	Number of homes	%
Number of commercial properties to be connected by the microgrid	30	66.67%
Number of commercial properties to be connected by the microgrid	12	80.00%

	£
Total CAPEX (post subsidy)	4,760
Total OPEX (post subsidy)	7,292
Total REPEX and any upgrades (post subsidy)	8,240

Levelised Cost of Energy (LCOE) 0.0119244 £/kWh

OPTION 1 - FIXED RATE

Has a fixed cost been considered for the community **Yes**

Option 1 - Fixed cost per residential rate	5.000	£/dwelling/month
Option 1 - Fixed cost per commercial dwelling rate	5.000	£/dwelling/month

Pre-tax Net Present Value (25 year) - option 1 **13,874** £

Pre-tax Internal Rate of Return (25 year) - option 1 **34.33%** %

OPTION 2 - per kWh charges

Has a per kWh price been considered for the community **Yes**

Option 2 - Per kWh consumed for residential	0.200	£/kWh
Option 2 - Per kWh consumed for commercial	0.200	£/kWh

Pre-tax Net Present Value (25 year) - option 2 **91,115** £

Pre-tax Internal Rate of Return (25 year) - option 2 **180.48%** %

OPTION 3 - Per kWh and Fixed Cost Charges

Has a per kWh price and fixed cost been considered for the community **Yes**

Option 3 - Fixed cost for residentials	2.000	£/dwelling/month
Option 3 - Fixed cost for commercial	2.000	£/dwelling/month
Option 3 - Per kWh consumed for residentials	0.150	£/kWh
Option 3 - Per kWh consumed for commercial	0.150	£/kWh

Pre-tax Net Present Value (25 year) - option 3 **169,001** £

Pre-tax Internal Rate of Return (25 year) - option 3

Carbon analysis

	Primary commercial fuel used	Total lifetime emissions saved by move to microgrid (kgCO2)
Commercial	Kerosene	145,314
Residential	Kerosene	363,285

By moving to a renewable grid **111** number of cars worth of emission (as of 2018) can be

Compared to the current grid **155** number of cars worth of emission (as of 2018) can be saved in its lifetime

Economic benefit (lifetime) for the local community when moving from current fuel to a microgrid

Option 1 - Fixed rate	3,716,496	£
Option 2 - per kWh charges	3,487,398	£
Option 3 - per kWh charges and fixed cost	3,273,929	£

<< To Input Menu >>

General | Plant Expenditure and Info | Revenue & Electricity Consump | CO2 inputs | Output>> | Results | Calculation>> | Time | Sheet1 | En

Appendix V

Reference links for publications:

https://www.mdpi.com/1996-1073/12/10/2008

energies
MDPI

Article

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

Abhi Chatterjee [1,*], Daniel Burmester [1], Alan Brent [1,2,*] and Ramesh Rayudu [1]

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[2] Department of Industrial Engineering, and the Centre for Renewable and Sustainable Energy Studies, Stellenbosch University, Stellenbosch 7600, South Africa
[*] Correspondence: abhi.chatterjee@ecs.vuw.ac.nz (A.C.); alan.brent@vuw.ac.nz (A.B.)

Received: 1 May 2019; Accepted: 22 May 2019; Published: 25 May 2019

check for updates

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

Energies **2019**, *12*, 2008; doi:10.3390/en12102008 www.mdpi.com/journal/energies

https://ejournal.undip.ac.id/index.php/ijred/article/view/22942

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Contents list available at IJRED website

Int. Journal of Renewable Energy Development (IJRED)

Journal homepage: http://ejournal.undip.ac.id/index.php/ijred

Research Article

Microgrids For Rural Schools: An Energy-Education Accord to Curb Societal Challenges for Sustainable Rural Developments

Abhi Chatterjee[a]*, Alan Brent[a,b], Ramesh Rayudu[a] and Piyush Verma[a,c]

[a] Sustainable Energy Systems, School of Engineering and Computer Science , Victoria University of Wellington, Wellington, 6140, New Zealand

[b] Department of Industrial Engineering, and the Centre for Renewable and Sustainable Energy Studies, Stellenbosch University, 7600, South Africa

[c] International Energy Research Centre (IERC), Tyndall National Institute, Cork, Ireland

ABSTRACT. Quality education and schools have a key role to play in the sustainable development of society. Unfortunately, many remote communities in developing countries fail to enjoy access to quality education due to a lack of electricity, thereby interrupting regular school services in the villages. The main objective of the paper contributes to understanding the importance of the energy-education accord, and aims to curb the social challenges prevailing in the villages. Specifically, the paper suggests a technical intervention by designing a hybrid renewable energy system for such schools. The approach is demonstrated through a case study with a load demand of approximately 4 kWh/d, comprising a class size of 40 students. A techno-economic evaluation of the energy system reveals the levelized cost of energy of the system at USD 0.22 per kWh, which may be affordable considering number of other aspects, outlined in this paper, to enable a larger uptake of such systems in developing countries.

Keywords: microgrids, rural electrification, rural school and education, techno-economic analysis, sustainable development goals

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How to Cite This Article: Chatterjee, A., Brent, A., Rayudu, R. and Verma, P. (2019. Microgrids for rural schools: An energy-education accord to curb societal challenges for sustainable rural developments. International Journal of Renewable Energy Development, 8(3), 231-241.
https://doi.org/10.14710/ijred.8.3.231-241

1. Introduction

The United Nations Development Program (UNDP) aims for affordable and clean energy access (Aggarwal et al., 2014), and sustainable, decentralized systems have gained importance across the globe for the provision of access to electricity (Energy Information Administration, 2040; *IEA webstore. WEO-2017 Special Report: Energy Access Outlook*). Specifically, the decentralized systems have emerged as a leapfrogging approach over the decades for the provision of electricity to the remote locations of developing nations, where the access to centralized grid services are afflicted due to many challenges (Hiremath, Kumar, Balachandra, Ravindranath, & Raghunandan, 2009; van Gevelt et al., 2018). Moreover, other factors, governing a paradigm shift towards a renewed interest in decentralized systems, have been the result of improved and efficient performances of the power technology equipment paring with the appliance costs (Barman, Mahapatra, Palit, & Chaudhury, 2017; Bensch, Peters, & Sievert, 2017; Louie, 2016; Mentis et al., 2015; Rojas-Zerpa & Yusta, 2014). Also, higher installation and maintenance costs of the conventional transmission and distribution systems, with an inclination towards the notion of 'sustainable energy democracy', have resulted in growing interests towards small-scale energy systems (Burke & Stephens, 2017; Mandelli, Barbieri, Mereu, & Colombo, 2016), especially for those deprived of basic electricity access ("WEO 2018).

Literature review

The scientific literature has addressed the issue with a focus on effective ways of energy source utilization techniques for small scale generations (Arto, Capellán-Pérez, Lago, Bueno, & Bermejo, 2016; Herington, van de Fliert, Smart, Greig, & Lant, 2017; Riva, Ahlborg, Hartvigsson, Pachauri, & Colombo, 2018). For instance, Rojas-Zerpa and Yusta examined the energy models, which can mathematically be utilized for rural electrification by introducing new paradigms for remote electricity evaluation criteria (Rojas-Zerpa & Yusta, 2014). Also, in the developing countries like India, Bangladesh and Malaysia, with a high prevalence of un-electrified villages (EIA, 2016; International Energy Agency (IEA), 2017), substantial efforts by the nodal renewable development agencies towards acquiring electricity for the rural despondent are evident (Palit and

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https://ieeexplore-ieee-org.helicon.vuw.ac.nz/document/8378470

Techno-Economic Analysis of Hybrid Renewable Energy System for Rural Electrification in India

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***Abstract*— This paper discusses a Hybrid Renewable Energy System (HRES) on basis of energy resources available for the location. The technical reliability and economic feasibility of HRES for a single household in an off-grid location is analyzed. The HRES modelled for the house constitutes a 100 percent renewable fraction and is proposed to serve a load demand of approximately 2.835 - 4.965 kWh/d over the three seasons. The results obtained reveal that HRES has the potential to overcome the issue of intermittent power and can balance load demand throughout the year by reducing unmet load and capacity shortage for the household at the same time being an economically feasible solution in terms of cost of energy studied over a projected lifespan of 25 years. This analysis is first of its kind in the state of Jharkhand, India and can be used as a framework to improve electricity infrastructure in electricity deprived communities.**

***Keywords*— HRES, unmet load, capacity shortage, state of charge (SOC), net present cost (NPC), cost of energy (COE).**

I. Introduction

Energy is accepted as intrinsically linked with environmental, social and economic dimensions of sustainable development. Providing reliable and secure electricity supplies, reducing environmental impacts and providing access to electricity to all have been recognized as the key challenge for all the electricity sectors globally [1]. Energy management is thus one of the most important aspects any government has to deal with [2]. Individually, rural sectors or hamlets may not be very important energy markets with sensible critical mass, but taken together, they are presently the largest niche market in the world for renewable energies (RE). In fact, at present, the largest percentage of the RE in the energy balance is also to be found in villages and rural areas [3].

On the other hand, the progresses made by rural sectors in developing countries are often found to be inefficient and inappropriate as they often become non-functional after few years of installation due to variety of reasons. There are also political, financial, legal and knowledge barriers preventing the optimum exploitation of renewable energy technologies(RETs), which must be overcome in order to create a favorable socio-economical and technical environment for electrification in rural sectors [4], [5]. In this regard in-depth study on techno-economic aspects of RETs for electrification in rural sectors for providing clean reliable energy is important [6].

As per the Government of India's 2006 rural electrification policy, a village is deemed 'electrified' if basic infrastructure such as distribution transformer and distribution lines has been set up in the inhabited locality, including a 'Dalit Basti' [7]. If government data is anything to go by, nearly all villages in the country or 98.7 per cent of them, to be precise have been electrified. But a closer look at the electrification data from the hinterland especially from states such as Bihar, Uttar Pradesh, Assam, Jharkhand and Odisha show that a sizeable number of the households in villages across most states are still in the dark, without access to electricity [8]. Approximately one-third of the populations living in India do not currently have access to electricity, and most of these individuals reside in rural areas [9].

The Indian government has declared that one of their core priorities is to provide electricity to every household in India[10]. While gradual progress has been made in extending the central electricity grid, reaching all rural households through such efforts is not a viable solution. A promising approach to the challenge of rural electrification is to increase the deployment of decentralized energy generation through the use of microgrids, which refers to a smaller-scale electric grid combined with a local generation source [11], [12].

The focus of this paper is to scale up the deployment of microgrids in all those villages where it is deemed the best option for rural electrification. It is essential to ensure that microgrids projects are both technically reliable, financially feasible and socially sustainable. In order to achieve this the steps of analyzing a microgrid project for any location is carried out in chronological order described below:

1. Assessment of Resources
2. Selecting System Parameters
3. Load Profile Assessment
4. Technical Assessment
5. Economic Assessment

This paper presents the technical and economic assessment of a HRES for a single household with a load demand of approximately 4kWh that can be utilized as a framework to provide electricity in village named Sapra, Jharkhand, India. The HRES system consists of PV, wind and a suitable storage unit making the system 100 % renewable energy based system.

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Distributed Generation for Electrification of Rural Primary School and Health Centre : An Indian Perspective

Abhi Chatterjee*, Alan Brent, Ramesh Rayudu
Sustainable Energy Systems, School of Engineering & Computer Science, Victoria University of Wellington, Wellington, New Zealand
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***Abstract*— The research focuses a Hybrid Renewable Energy System (HRES) for the electrification of a rural school and a health centre for a rural site in India. The HRES modelled for 100 percent renewable resources serves a load requirement of approximately 3.38-4.28 kWh/d for the school and 6.55-8 kWh/d for the health centre, based on varied seasons. The microsystem model is designed for a 25 year projected lifespan, to balance the required load for energy deprived schools and health centres in rural areas of India. Of an utmost importance is to overcome the issue of intermittent power and reducing unmet load, and improving the autonomy of the system. This analysis can be used as a framework to improve electricity infrastructure in electricity deprived communities of the developing countries; thus improving social well-being of people from an engineering aspect.**

***Keywords*— HRES, rural electrification, microgrid, cash flow analysis.**

I. INTRODUCTION

In any developing country the major encumbrance to social and economic growth is a consequence of energy shortage [1]. Despite efforts by federal and provincial governments to improve electricity access and services over the last five decades, rural electrification lags behind due to various aspects. These can be either for its geographically inaccessible terrain of location, or sporadic policies. India is being predominantly considered a rural country with around 67 per cent of the population living in villages [2]. As per the data acquired from the World Bank [3], there has been a fall in the rural population due to large-scale migration from rural villages to cities due to a push-pull factor. This fall in rural population is attributed to migration of people from rural to urban cities in search of better socio-economic status.

The lack of socio-economic status can be attributed to as lack of basic medical and health facilities, inadequate education facilities, and also lack of regular income. The causes of these factors can be intrinsically linked to one major factor, namely the lack of reliable and affordable energy service to dwellings in remote villages.

For an overall development of the country, a major emphasis needs to be given to rural electrification [4] to check the issues of the increasing migration and existing socio-economic issues existing in rural villages. The impact of rural electrification [5, 6] can be classified as quantifiable and unquantifiable. The authors in [6], [7] suggests the quantifiable benefits of electricity, which includes increased productivity for industrial and commercial usage of electricity with household use for lighting, cooking and also for water pumping applications in agricultural fields. However, the unquantifiable benefits that are difficult to quantify can be considered as the modernization and dynamism for a standard quality of life, increased community services and participation, equity in income distribution and social equity with creation of employments.

In most cases the benefits that are difficult to quantify are neglected. As a result of which, poverty, poor health and illiteracy prevails. As one study states, electricity "allows the access of lower-income people to lighting, communication, as well as a variety of educational delivery opportunities. A major impact of electrification has been reducing illiteracy and improving the quality of education." [8] As per a report in 45 developing countries, the literacy rates tend to be lower among the youth in rural villages [9]. The presence of electricity results in improved quantity and quality of life. As India has the highest population of youth population [10] it is necessary to have basic education in rural villages. Another aspect of social life is the basic health facilities being provided to the rural populations, which can bring about the overall modernization of society by adding quality to life.

Although household electrification has been the major attention of policy-makers and the government, the other basic factors for socio-economic development are often neglected. This paper, however, addresses this issue and focuses on scaling up the deployment of micro-grids for the energy dearth rural communities. The authors in this paper, have tried to provide a clean source of uninterrupted and reliable power to a primary school and health centre in an energy deprived village of Jharkhand, India.

This paper presents a techno-economic analysis of an HRES for a primary school with a load demand of approximately 4.3 kWh, and a health centre with a load demand of approximately 7.5 kWh. This study can be used as a framework for electrification in a village for basic education and health care facility. The HRES system constitutes a PV, wind turbine, and battery as a storage system towards a 100 % renewable energy system.

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Defining a remote village typology to improve the technical standard for off-grid electrification system design

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***Abstract*— Access to affordable and clean energy to the rural communities in the developing nations has been the pivotal aim on a global stage. Universal access to reliable and clean electricity to the ever-increasing global population has directed the governmental bodies to switch towards a decentralized energy access approach. However, the efforts of the nodal agencies around the world have not yielded the desired results. A knowledge gap in terms of a village typology that corresponds to an inappropriate electrification system selection has been identified. A suitable typology for remote villages in developing countries is subsequently defined for rural electrification system classification. Also, amendments to the technical standard IEC/TS 62257-2 for rural electrification are suggested, which is decisive in the techno-economic assessments of microgrids in such contexts.**

***Keywords*— Rural electrification, village typology, technical standards, microgrid**

I. INTRODUCTION

An introduction to the Agenda 2030, for a global sustainable development, led by the UNDP in 2015, was established with an objective to transform the world [1]. The Commission of the Councils, after various stages of improvisation for a destined outcome, recognized an ambitious intent for poverty eradication and sustainable development as a global vision. The Agenda, with an inclusion of the 17 sustainable development goals (SDGs) and 169 targets are desired to pave the way for a prosperous and to ensure an equal sustainable development path for all the people globally by the year 2030 [2]. However, SDG7, for affordable and clean energy access, has been considered as an intrinsic and a pivotal indicator responsible for a nation's overall economic growth and human development index [3]–[5]. SDG7, with its aim to ensure universal access to a reliable energy services and increase share of renewable energy in the global energy mix by 2030, holds an apex position among the other SDGs [3]-[4]. However, provision of a reliable and an affordable electricity access holds the cusp of the energy access hierarchy among the other factors associated with energy access, such as energy for cooking and heating [8]–[13].

Over the decades, varied efforts have been undertaken by the governmental and the non-governmental nodal agencies across the globe, to ensure expansion of electricity infrastructures by means of extension of the centralized grid [14]. Although the efforts have yielded a substantial result in the developed countries, the scenarios in the developing countries have been unsatisfactory. The UNDP highlights one in five people around the globe still lack access to modern electricity, and the World Energy Outlook 2018 reports an electricity demand to grow twice the pace of the energy demand as a whole [15].

In order to compensate the people devoid of electricity across the globe, a growing interest in the use of a decentralized energy system (DES) has been observed [16], [17]. These systems range from a picowatt to megawatt level with varied applications [18].

A research article indicates a techno-economic analysis (TEA) for the developing countries as a prolonged practice for off-grid system assessments [18]. The conventional TEA, which generally constitutes a 5-step approach towards a microgrid model development, is based on the international technical specification standard IEC/TS 62257 [19]. A shortfall in the standard lies in an inefficient typology identification and classification of the rural electrification systems. The incompetency in the technical standard for a TEA has led to a degradation in the value proposition of microgrids and deployments for end use applications [20]-[21].

The literature indicates academic research on developing the building typologies for urban scenarios, archetypes and benchmark models, but these typology identifications cannot be replicated in the rural electrification scenario for developing countries [22]. Furthermore, the technical specification standards developed for the rural electrification systems delivers a complex methodology for typology

Appendix VI

The matrix scale for the attributes of the MTF are indicated below as adopted from [132].

Availability attribute scale

Indicator	Tier 0	Tier 1	Tier 2	Tier 3	Tier 4	Tier 5
Hours available per 24 h period	–	≥ 4 hours		≥ 8 hours	≥16 hours	≥ 23 hours
Hours available per evening	–	≥ 1 hours	≥ 2hours	≥ 3 hours	≥ 4 hours	

Reliability attribute scale

Indicator	Tier 0	Tier 1	Tier 2	Tier 3	Tier 4	Tier 5
Number of disruptions/week	–	–	–	–	≤ 14	≤ 4 AND aggregate duration < 2 hrs/week

Affordability attribute scale

Indicator	Tier 0	Tier 1	Tier 2	Tier 3	Tier 4	Tier 5
Cost of consuming 365 kWh/year	–	–	–	< 5% of annual income		

Legality attribute scale

Indicator	Tier 0	Tier 1	Tier 2	Tier 3	Tier 4	Tier 5
Bill Payment	–	–	–	–	Paid to supplier or authorized agent	

Health and safety attribute scale

Indicator	Tier 0	Tier 1	Tier 2	Tier 3	Tier 4	Tier 5
Wiring installed per national standards	–	–	–	–	Paid to supplier or authorized agent	

Quality attribute scale

Indicator	Tier 0	Tier 1	Tier 2	Tier 3	Tier 4	Tier 5
Voltage	–	–	–	–	Voltage is within the parameters specified by the grid code	