Sustainable microgrids for remote communities: A practical framework for analyzing and designing

Alan Brent (alan.brent@vuw.ac.nz), Abhi Chatterjee (abhi.chatterjee@nz.ey.com), Daniel Burmester (daniel.burmester@vuw.ac.nz), Ramesh Rayudu (ramesh.rayudu@vuw.ac.nz)
Sustainable Energy Systems, Faculty of Engineering, Victoria University of Wellington, New Zealand

Abstract
Decentralized microgrid systems have provided electricity to off-grid communities, devoid of the necessary energy services, for a number of decades. However, in many instances microgrid systems have failed in delivering sustainable electricity supply. This has resulted in communities, primarily residing in remote or islanded areas of developing countries, having lower social and economic resiliency compared to the urban areas with centralized grid connectivity. The lack of a detailed standard framework, for cross-sectional evaluation of the sustainability and reliability of microgrid systems, has been identified. This chapter then introduces a conceptual framework to improve the design of remote microgrid systems. The framework comprises of modules that incorporate essential features, such as stakeholder engagement, sustainability aspects, energy management, and improving energy efficiency, as well as overall system autonomy – when undertaking the analysis and design of microgrids. The process, to make the framework practical, was established through the Working Group on Sustainable Energy Systems for Developing Communities (SESDC) of the Institute of Electrical and Electronics Engineers (IEEE). The outcomes when applying the framework, and associated process, are demonstrated with a case study in India. The outcomes show the contribution of the practical framework in attaining sustainable development goal number seven (SDG7) – enabling clean electricity access for remote communities – and supporting the Sustainable Energy for All initiative of the United Nations, and the Smart Village initiative of the IEEE – to improve the resilience of these communities.

Keywords
Sustainability, renewable energy, microgrids, off-grid, rural communities.

1. Introduction

The International Energy Agency (IEA 2020) highlights that modern energy services are crucial to human well-being and to a country's economic development. To aid the progression to modern energy services the United Nations Development Program (UNDP 2020) introduced the Sustainable Development Goals (SDGs) with the 2030 Agenda. This global action for local results, with an emphasis on remote regions, is based on the achievement of access to affordable and clean energy (SDG7) (UNDP 2020).

The drive for universal access to electricity has, primarily, resulted in technological advancements in the generation, transmission, and distribution of electricity. The endeavor for access to electricity has, however, been challenging in developing countries, and especially so for remote regions (Haghighat Mamaghani et al. 2016). The expansion of electricity has not been uniform, with the consequence of many remote communities having a lower social and economic resilience compared to urban areas. It is, indeed, the case that the intention of a centralized electricity grid approach to bridge the gap between rural and urban contexts faces challenges owing to various demographic, topographic, social, and economic factors (Palit & Chaurey 2011, Chandel et al. 2016, Bhattacharya et al. 2016).

A decentralized approach, in the form of microgrids, has subsequently been recognized and used over decades, for various purposes. This decentralized approach is an alternative to the centralized grid infrastructure to serve the purpose of end-users of more remote communities. Microgrids save on extensive capital investments for the maintenance of aging transmission and distribution infrastructure for sparsely populated regions (Gui et al. 2017), and have additional environmental benefits if local, renewable energy resources are utilized (Pepermans et al. 2005).

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 decentralized off-grid, microgrid systems compared to the conventional ways of electricity access. Nevertheless, a review of the literature (Sawle et al. 2018) 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 addition to the technical and economic challenges emphasized by various literature sources, the social factors are equally crucial in these projects (Sawle et al. 2018). The energy system challenges generally indicate a lack of understanding the dynamic interaction of the energy system with the wider community system, and a misalignment with societal development objectives (Akinyele et al. 2018). There is a distinct difference between energy provision that improves living conditions, such as lighting, and energy provision that enables productive activities. Only with the latter will economic and social transformation occur, which, in turn, entail different behaviors and energy consumption patterns. Thus, the microgrids have to cater for all the community's needs, which can be electrified, and that evolve over time. This requires a change in paradigm with respect to microgrid utilization, which should form part of the power systems design process, although social and developmental aspects are rarely considered in such (techno-economic) practices.

The objective of the chapter is then to establish a practical framework to improve the analysis and design of remote microgrid systems that addresses the shortfalls of current techno-economic approaches. Such a framework needs to address the following (Sawle et al. 2018, Chatterjee et al. 2019):

- Electrification planning techniques: An effective pathway towards examining each individual electrification system or load estimation, instead of a total average load estimation, as part of a collective electrification system for the entire village, can be seen as a way forward towards a "unified electricity approach" in the remote communities. This then depends on the services required, rather than considering an inventory average distribution of electrification for the entire village.
- Energy utilization and management techniques: Various cases report that failures occur due to inadequate power generation in a non-hybrid resource-based system. This leads to a technically unstable and economically unfeasible electricity solution over the project lifetime. A proper energy mix for the resources, involved in the process of power generation for the system, will yield to better management of the resources. Also, proper resource management would augment the service life and performance of the

system parameters. Furthermore, an active effort in proper energy utilization and management would ensure an overall reduction in replacement time of the storage units and an effective cash flow, resulting in an escalation of the salvage value of the system parameters at the end of the project lifetime.

- A resilient approach for microgrid systems: The autonomy of the system, which has been neglected in the literature, is suggested to have a substantial impact on the overall reliability aspect of the microgrid system. A microgrid, without a system autonomy approach, would still be able to balance the load requirement for standard operating conditions, but inadequacies arise in events of power outage due to a fault in the power system components or in events of natural catastrophes. A resilient approach towards microgrid design, accounting for irregularities, can be seen as a fundamental task for an uninterrupted power generation to the end use application.
- Considering system dynamics: The generation of power, with the use of renewable energy for the electrification, can vary due to the intermittency and variation in the sources. Also, the effect of changes in the energy ladder plays a vital role in the overall system performance over the project lifetime. In order to prevent jeopardizing the system lifetime, a sensitivity analysis of the microgrid system should be performed to analyze the impact of the variations arising in the system. The variations 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.
- Technology adoption: In order to prevent microgrid failures and enhance the acceptance of the system, technology adoption plays a vital role. These technologies would be directed towards ensuring the engagement and participation of the end users in the pre-post project phase. The involvement of the end users, project developers, project consultants and implementers, prior to the system implementation, would likely establish the liabilities during the system scoping process. Also, post-implementation, the duties and the responsibilities of the stakeholders can be established for the successful operation, maintenance and replacement of the system over the project lifetime. The technology adoption process, in addition to technical aspects, should ensure the awareness regarding social and cultural implications, environmental impacts, infrastructure security, and critical issues of power theft.

2. Conceptual framework for the design of sustainable microgrids

Chatterjee (2020) developed a conceptual framework to improve the design of sustainable microgrid systems for off-grid, remote communities in developing countries, based on a review of literature (Chatterjee et al. 2019). Figure 1 illustrates the convergence of the elements associated with the conceptual framework that would lead to the attainment of an overall sustainability-oriented approach.

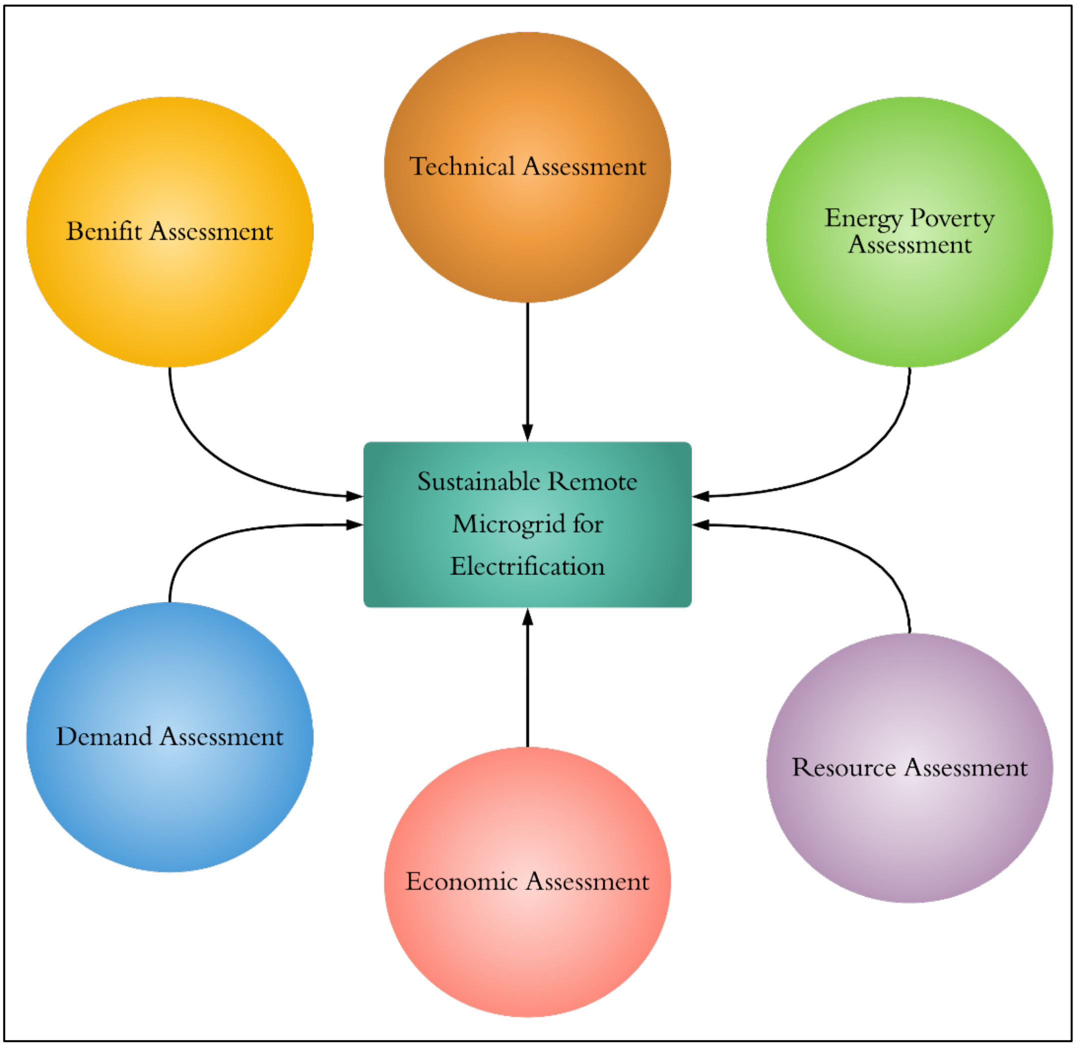

Figure 1. Required convergence of elements to design sustainable microgrids

The proposed framework has several features that are distinct from traditional electricity and energy planning frameworks. 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. 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, community level. Fourth, the framework focuses on essential aspects of energy management, as well as the benefits of energy access programs, for improving the overall social well-being and environmental quality, and other relatable SDGs.

Figure 2 provides an overview of the phases, and the considerations that are required in the associate modules.

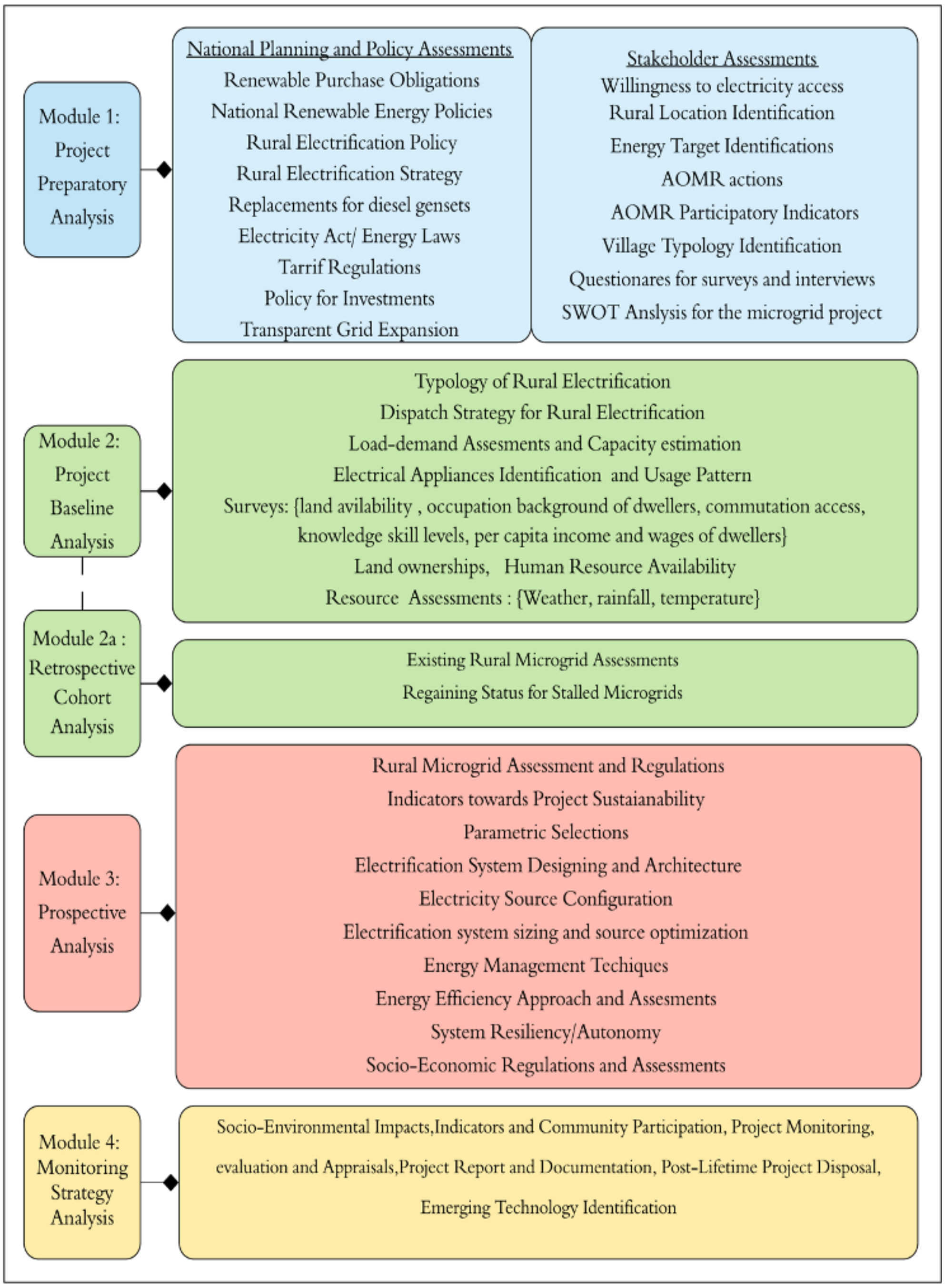

Figure 2. Modules and associate considerations of the conceptual framework

2.1 Module 1: Project preparatory analysis

Module 1 is the bedrock for a microgrid project, constituting the assessments of and for national policies, and stakeholder participation. National governmental plans and policies are an integral part of integrating microgrids 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 microgrids into the national electrification master plans, and primary electrification policies and strategies. Module 1 initially describes policies that can effectively encourage private-sector investment in microgrids, 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 the hindrance towards improving decentralized electrification in remote areas.

While most countries have national electrification plans, many of these plans may not include off-grid energy developments. 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 (EUEI 2014). The following vital elements incorporated in Module 1 of the conceptual framework could enable an increase in decentralized projects for remote communities (Chatterjee 2020):

- Renewable Purchase Obligations (RPOs);
- Renewable Energy Policies;
- Rural Electrification Policies;
- Plans for replacing diesel gensets;
- Tender and licencing procedures;
- Tariff regulations; and
- Rural electrification grants and subsidies.

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 remote 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. 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-centered 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. The MCS is inhabited by families and commercial activities such as banking, agricultural storage and trade centers, as well as public amenity centers. A combined electrification system (CES) can be considered suitable for LVP, CVP and MCS village typologies 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; in other words, islanded communities. A CES is key to such a typology where the electricity loads comprise of an entire village model: household, agriculture, semi-commercial activities, health centers, schools, religious centers, social and public amenity centers, as well as 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.

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 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 2 tabulates the AOMR participatory indicators and the activities involved for the project.

Table 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 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					

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 (Chen et al. 2014). 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 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.

2.2 Module 2: Project baseline analysis

The typology of rural electrification is classified based on the topology of the village identified in the previous module. The rural electrification scenario, as seen in Figure 3, is predominantly classified based on the purchasing power parity, qualitative electrification requirement, and the quantitative electrification requirement.

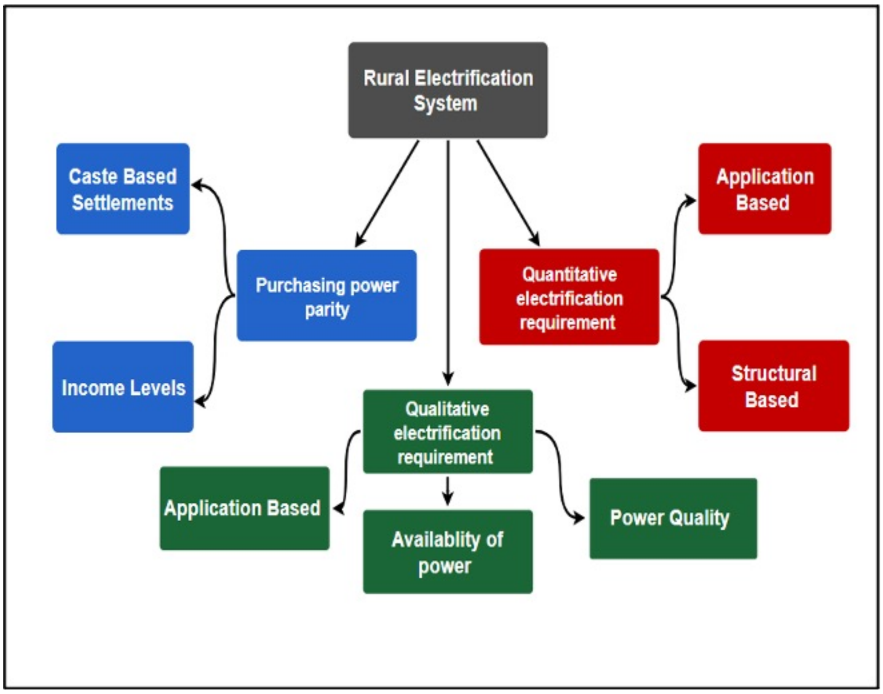

Figure 3. Typology of a rural electrification system (in the India context)

The purchasing power parity signifies the economic status of the community to purchase electricity for end-use applications. For developing countries, the poverty level, cultural segregation, and other aspects play a crucial role in determining the power purchasing capacity of an individual. The desired usage establishes the qualitative electrification requirement concerning the type of appliances for used activities such as for households (lighting, cooling, and entertainment), public access (street lighting, schools, and health centers) and economic activities (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.

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 technical standards also need to be consulted, which 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 (IEC 2015). The IEC/TS 62257-2 constitutes a generic technical specification (TS) for the renewable energy electrification ranges and the typologies and has negated the importance of the remote electrification of developing countries.

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 in terms of 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, and other education services), public institutions (such as government offices, religious buildings), and infrastructure services (such as water supply and street lighting).

A detailed assessment and knowledge of available energy resources and their associated development are crucial 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. Furthermore, the resource assessment provides information about other important aspects of resources; for example, 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 are based on the:

- Availability of resources: 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: Refers to whether enough resources are available to meet the energy demand 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: Considers whether one resource is more sustainable than others from an environmental, health, energy security and economic standpoint.
- Ease of access to resources: Refers to the effort required to obtain the resources.
- Cost of resource use: The value of using a resource to provide access to essential energy services.

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.

2.3 Module 2a: Retrospective Cohort Analysis (RCA)

In the conceptual framework, a Retrospective Cohort Analysis (RCA) is introduced to analyze existing microgrids in rural communities. The use of an RCA would help in determining the functional status of the existing microgrids, where underpinning microgrids were identified based on CAARLS attributes, namely: capacity, availability, affordability, reliability, legality, and sustainability (Chatterjee et al. 2019). The use of an RCA would enable the failed microgrids to regain normalcy.

2.4 Module 3: Prospective analysis

Module 3 entails 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 – present and future.

Considering the aspect of sustainability, with a complete reliance on using renewable resources for the microgrid system, it is of vital importance to understand the functional description of the energy management system for the remote 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. Figure 4 illustrates the energy management role and the component functionality in a microgrid system.

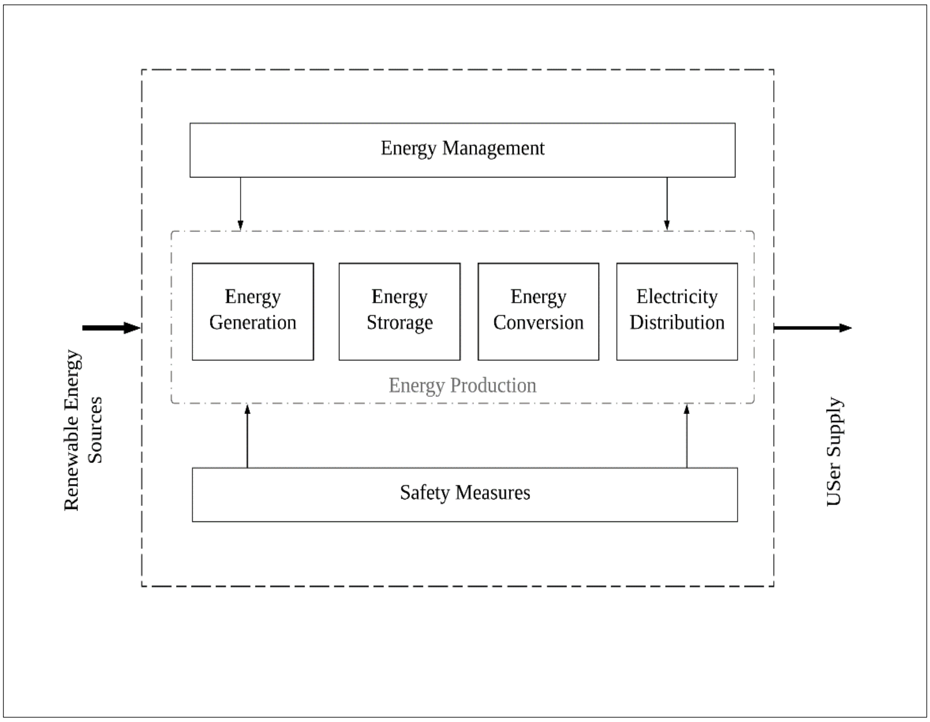

Figure 4. Functional impact of an energy management system

To effectively manage energy in microgrid systems, several functions need to be considered:

- Adequate management of resources and needs: To efficiently manage energy in an isolated system, consideration needs to 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.
- Maximizing service life and performance of equipment: Managing energy in an isolated system 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. In particular, the quality of battery management has a very high impact on battery life, on the system's level of performance and life cycle cost.

The autonomy of the system has been shown to have a substantial impact on the overall reliability aspect of the microgrid system (Chatterjee 2020). 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 (Louie 2028). However, a 3-day autonomy is normally considered to account for factors of power insurgency due to technical or system faults, but not natural disasters or catastrophes (Chatterjee 2020). A system designed using more days of autonomy will have higher reliability. However, increasing the autonomy increases the required storage capacity and increasing system cost, although the reliability does not necessarily proportionately scale with the days of autonomy.

A resilient approach towards microgrid design that accounts for irregularities is a fundamental task for an uninterrupted power generation to the end-use application. To this end, system dynamics 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 analyze 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.

A proper system sizing is also required. A systematic microgrid system sizing, adapted and further revised in accordance with 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. This important, because financing microgrids in developing countries is challenging (Troost et al. 2018). Microgrid projects typically require long-term funding with a low cost of capital. Banks and nodal agencies in 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.

The cost assessment provides 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 minimizes 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, 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.), and population density.

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 minimizes 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.

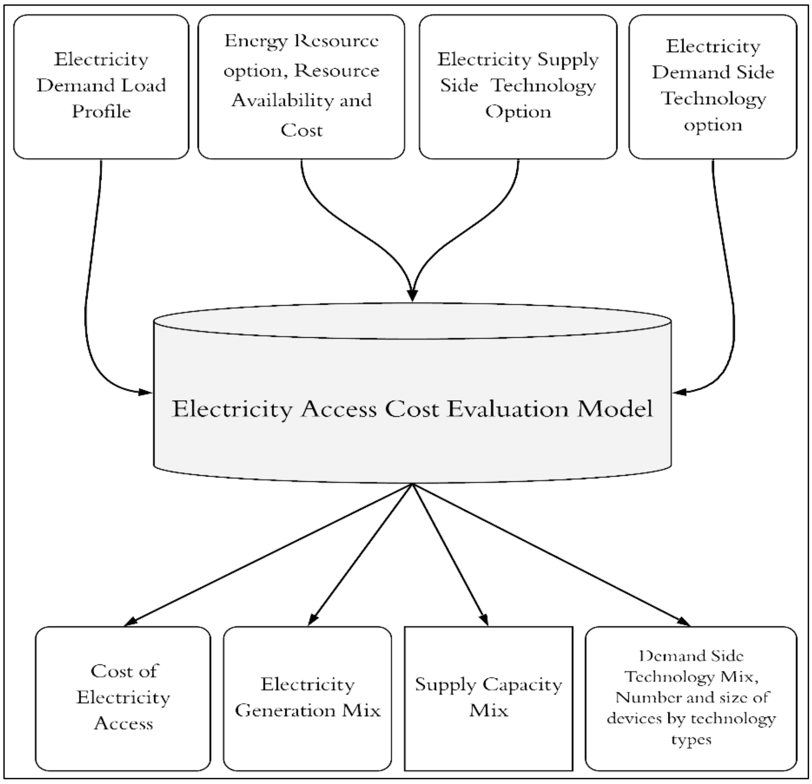

Figure 5. Strategic assessment of electricity access cost

Figure 5 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 upfront demand-side costs), electricity generation and capacity mix (by type of technology and energy resource).

2.5 Module 4: Implementation and monitoring analysis

The last module constitutes the implementation and monitoring strategies. In this phase, the project monitoring, following the AOMR actions (see Table 1), 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 to 25 years for remote microgrids.

3. Process to design sustainable microgrids

The Working Group on Sustainable Energy Systems for Developing Communities (SESDC) of the Institute of Electrical and Electronics Engineers (IEEE) provided further inputs to establish a process, or practical framework, to design sustainable microgrids (Chatterjee 2020). The Working Group "*aims to raise awareness to the technical community, governments, policymakers, and organizations about access to energy systems, including electricity and the related issues in developing communities around the world*" (SESDC 2020). The Working Group therefore aligns with the goals of Sustainable Energy for All initiative of the United Nations (2020), and the Smart Village initiative of the IEEE (2020). It comprises 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 working groups of the IEEE.

A process flow diagram was developed, as shown in Figure 6, which explains the various stages at which the modules established within the conceptual framework can be effectively utilized for improving the deployment of off-grid microgrids.

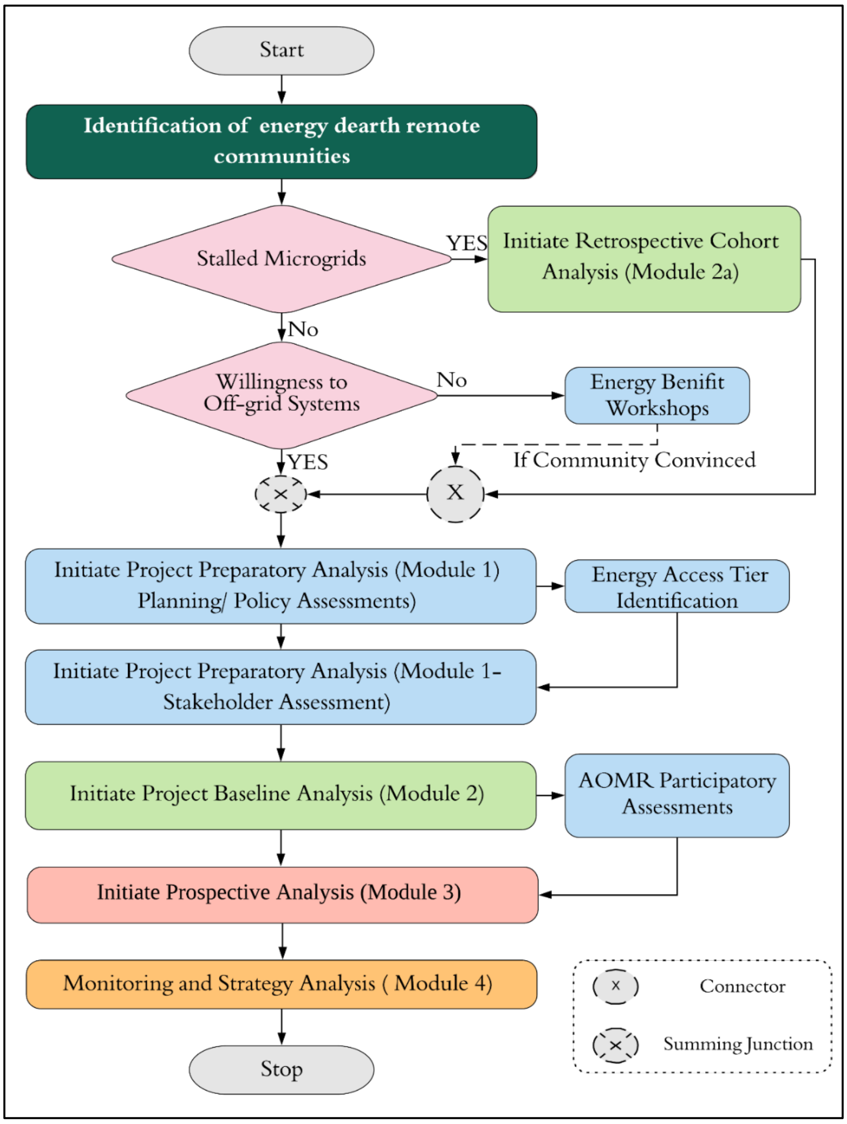

Figure 6. Process-flow diagram showing the incorporation of the modules of the conceptual framework

The process flow starts with identifying the location of the community that will be focused on. The locations are categorized in two scenarios:

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

The first scenario considers the complete absence of any off-grid systems available for electricity provisions. An essential step for involving the community is to ascertain their interest and willingness to develop an off-grid microgrid system. This step can be accompanied by training sessions or workshops to ensure the community is informed of the scope of the envisaged energy provision. On attaining the community approval, the activities, mentioned in the modules (Figure 2), can then be undertaken. 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 aspects that need attention.

The second scenario considers a community where a microgrid was implemented, but subsequently failed, leading to a non-functional state. The assessment activities can be enforced through Module 2(a) of the conceptual framework. 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. Application of the practical framework

The application of the practical framework, with an emphasis on Module 3 – the prospective analysis, is demonstrated with a case study; with 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 Figure 7.

Figure 7. Location of the village Sapra in India

The selected site distinctly experiences prolonged dry spells of summer (March – October), followed by winters (November-February). The village location is approximately 26 kilometers 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 (Sinha & Singh 2011). However, the village Sapra, separated from Jamshedpur by the 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.

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 were sourced from Surface Meteorology and Solar Energy database of NASA (2020). The highest PSH of 6.40 is obtained in April, while the lowest PSH value of 4.08 is 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 Figure 8. 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 Figure 9, with an anemometer height at 50 meters. Detailed analyses of the resources, with daily profiles, are provided in Chatterjee (2020).

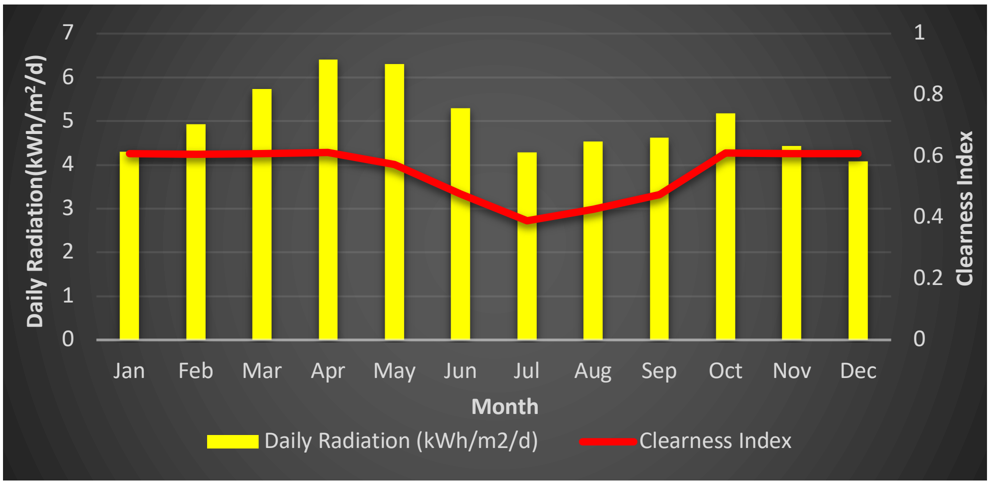

Figure 8. Solar resource at the location

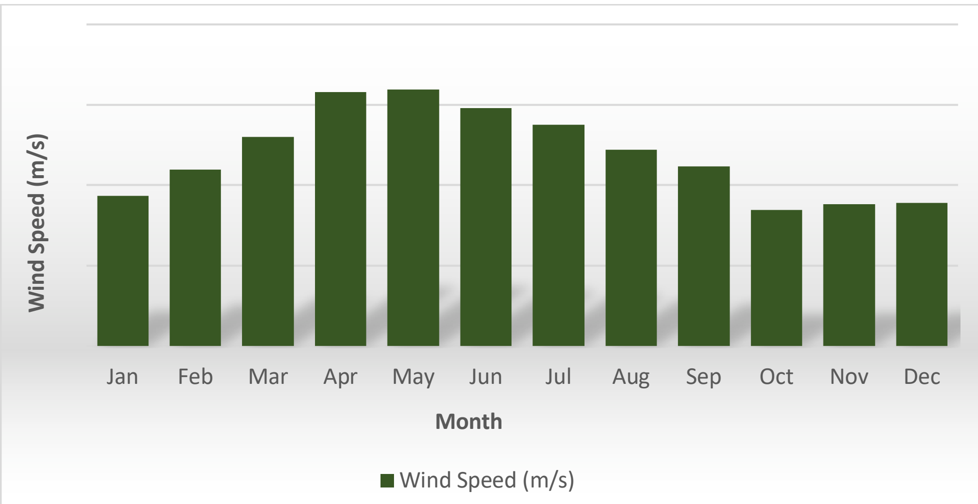

Figure 9. Wind resource at the location

4.1 Load classification for remote community electrification

A load profile estimation is fundamental to the design of a microgrid. In order to create a load profile, however, it is crucial to understand the lifestyle of the community, their electricity needs, and their energy usage pattern. Also, it is necessary to understand the additional energy requirements to augment their overall social well-being (Roy et al 2012). In order to ensure the development of the social well-being of the community, therefore, a load estimation pattern has to be strategically established as opposed to the conventional electrical load factor. A strategic distribution of load ensures uniform electricity access catering to the varied needs of community members. To this end, the units and the types of appliances are selected following energy-efficient approaches without compromising the basic needs of the community members. In view of this, the electrical load for a remote community is classified into three categories:

- High Priority Load (HPL) – Includes electrical loads for the domestic households, and essential services, such as health care and education.
- Medium Priority Load (MPL) – Comprises of the community street lights, community toilets, a community hall, and shops.
- Deferrable Load (DL) – Electrical loads that require a certain amount of energy within a given time period (in this case, the agricultural load for water pumping).

Furthermore, based on the load classification and the lifestyle of the community, for their electricity usage pattern, a day-to-day variation along with a time-step-to-time-step variation in the capacity utilization are considered.

The HPL, for the Sapra village, consists of the 20 households, with a health center and a primary school. Separate weekday and weekend 24-hour load profiles loads are defined for these entities. The consideration, designing separate load profiles, adheres to the variations in the lifestyle of the community members 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 CFLs and the incandescent bulbs with LEDs, considering several lighting loads based on standard building specifications for lux/square feet, and improved refrigerators for storing vaccines. The details of the electrical appliances for the various loads constituting the HPL are tabulated in Tables 3 to 5. 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 Figure 10. Similarly, a 24-hour season variation-based load profile for the MPL constituting the streetlights, community toilets, a community hall, and shops for a random day-to-day variability of 5 percent is shown in Figure 11. The DL is a 6 kW peak motor, requiring around 21 kWh per day.

Table 3. 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 4. Appliance description for the health center

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. Appliance description for the 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

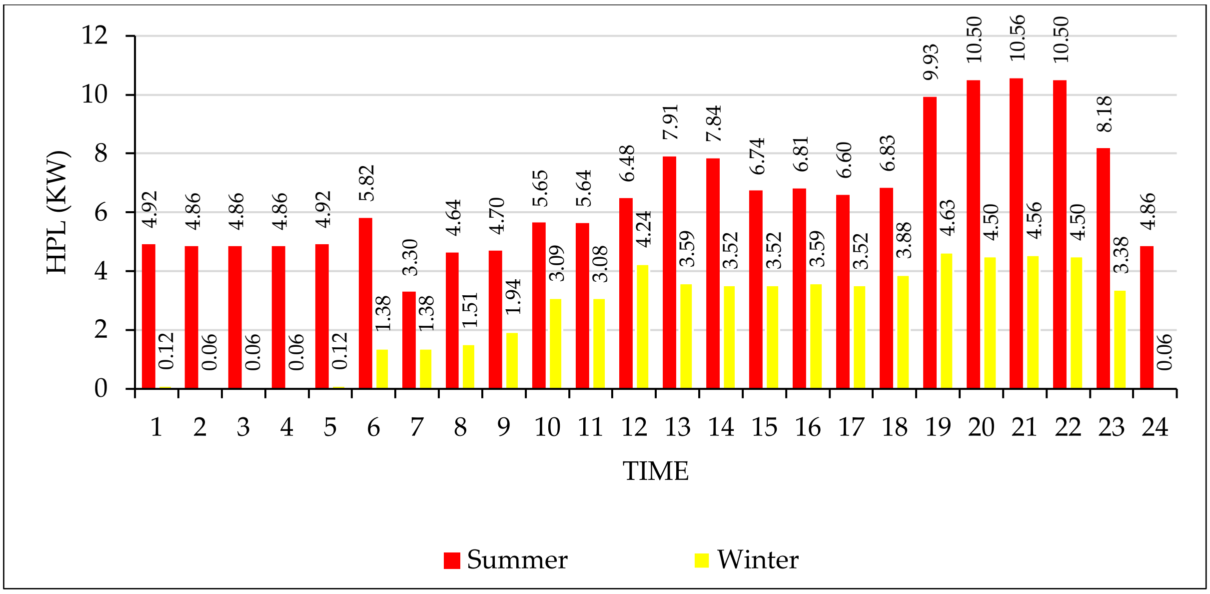

Figure 10. Seasonal variation based 24-hour load profile for High Priority Loads

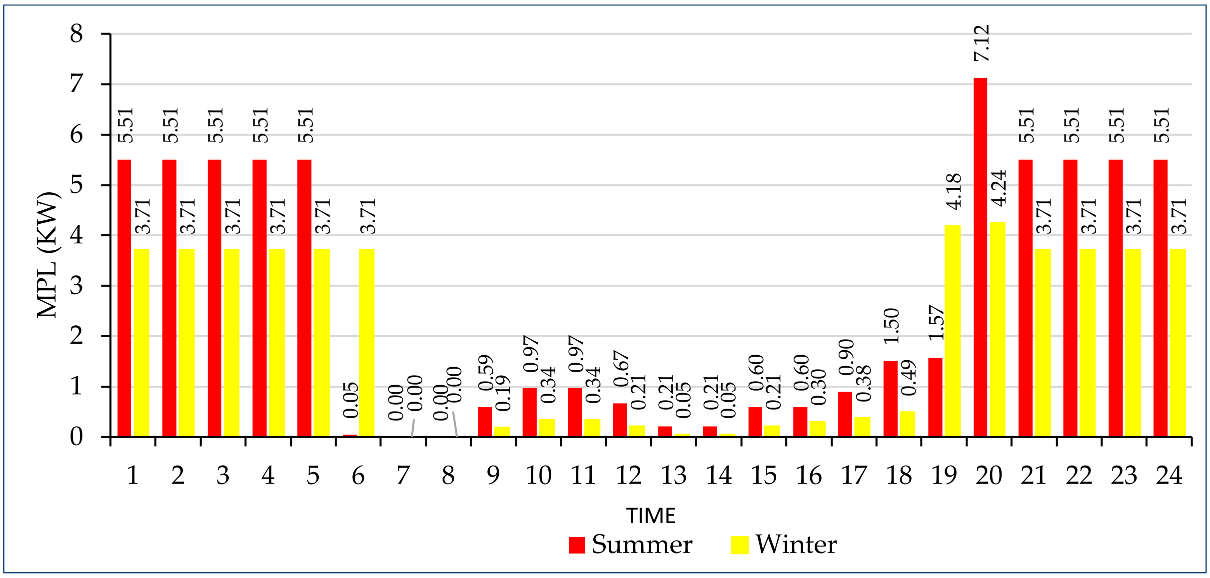

Figure 11. Seasonal variation based 24-hour load profile for Medium Priority Loads

4.2 Considering microgrid configurations

The step following the load profile improvisation is testing the various system configurations of the off-grid microgrid system (see Figure 12). During this process, off-grid systems are mainly classified into three main categories, with further sub-categorizations, based on the placement or incorporation of the system components for meeting the required electrical load. The effect of the system configuration classifications is further examined on the basis of an economic analysis – net present cost (NPC) and levelized cost of electricity (LCOE), and a technical analysis – excess energy (kWh/yr), capacity shortage (kWh/yr), and unmet load (kWh/yr)). The categorization of the system is as follow:

- A complete DC power-based system configuration with the options: hybrid system (PV+WT); PV only; or WT only.
- Deferrable Load (DL) connected to AC bus bar with the options: hybrid system (WT connected to DC bus bar); hybrid system (WT connected to AC bus bar); PV only; or WT only.
- Deferrable Load (DL) connected to DC bus bar with the same options as before.

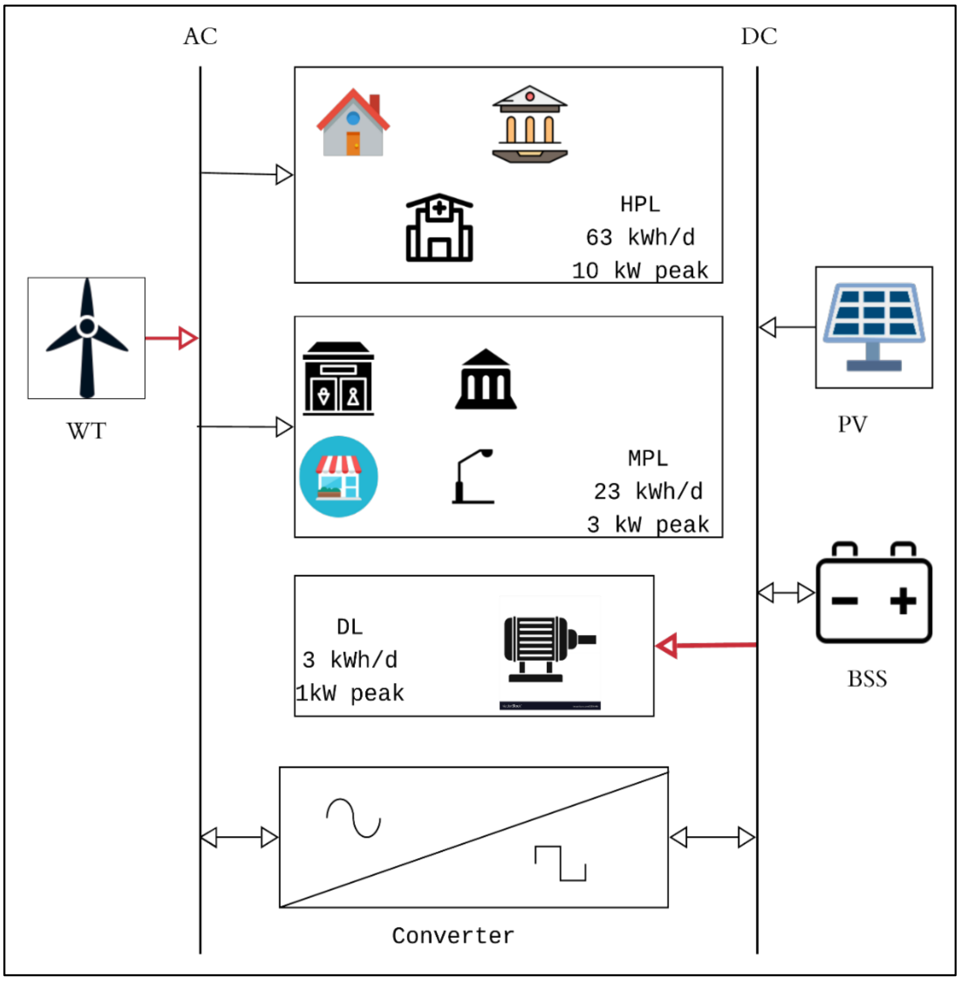

Figure 12. The architecture of a hybrid renewable energy based microgrid for remote electrification

4.3 System modelling

A variety of software packages are available to undertake the modelling and analysis of the different system configurations. Chatterjee (2020) provides the details of the modelling setup and characterization of the various parameters. The simulation follows a strategy for optimizing systems based on a technical feasible configuration sorted by net present cost (NPC).

As seen in Table 6, from the first configuration, considering an off-grid system to be a simple DC-based system, the results in the case of only PV and only WT indicated the systems to be economically implausible due to high a 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 indicated substantial system autonomy with lower capacity shortage, but the simulation found the system unsuitable owing to excessive dependence on the BSS. The over-dependence on the 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.

Table 6. Optimized techno-economic analyses for various system configurations of remote microgrid

System Configuration Types		System Parameters				Economic Analysis (USD)		Technical Analysis (kWh/yr)			Autonomy (hr)
		PV	WT	BSS	Conv	NPC	LCOE	Excess Energy	Capacity Shortage	Unmet Load	
DC System Only	Hybrid System (PV+WT)	20	6	140	0	82,325	0.19	37489	23.7	21	74
	PV only	41	0	172	0	110,845	0.26	34875	33	32	91
	WT only	0	90	528	0	311,202	0.73	558718	0.50	0.2	279
DL to AC Bus	Hybrid System (WT connected to DC Bus)	22	5	144	12	90,414	0.21	33370	31	29.5	76
	Hybrid System (WT connected to AC Bus)	22	4	152	12	89,928	0.21	26971	30	32	80
	PV only	42	0	188	15	122,335	0.29	34748	31	30	99
	WT only	0	65	592	15	277,446	0.65	390795	18	18	313
DL to DC Bus	Hybrid System (WT connected to DC Bus)	22	5	144	12	90,414	0.21	33442	32	29	76
	Hybrid System (WT connected to AC Bus)	22	4	152	12	89,927	0.22	26978	30	33	80
	PV only	43	0	184	15	122,340	0.29	35695	33	33	97
	WT only	0	65	592	15	277,441	0.65	390869	17	17	313

The other configurations, which considered the DL connected to the AC or the DC bus bar, again highlighted the necessity for a hybrid system with the WT positioned on the AC bus bar being the overall best option; although relying on a slightly larger BSS. However, with agricultural loads constituting brushless DC (BLDC) motors gaining popularity, a DL connected to DC bus bar with a hybrid system, and WT connected to the AC bus bar, 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 the system shown in Figure 12.

Chatterjee (2020) compared this designed system, the outcome of Module 3 of the framework and process, with that obtained from a conventional approach, which does not consider interventions to influence the load profile, or the variations of the load over time, after an effective engagement with the community (see Table 7).

Table 7. Comparison of a design outcome based on a conventional approach the introduced framework and process

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

4.4 Discussion

Based on these outcomes, and from further engagement with the community, the following is observed:

- 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 was to be followed, a microgrid needs a model to be designed considering a capacity shortage of 40 to 50 percent to match the NPC of a microgrid based on the introduced framework, 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.

Overall, the energy-efficient microgrid system for the village would contribute significantly towards the following purposes:

- Ensuring the accomplishment of efforts towards indicator 7.1.1 of the SDG 7 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.

5. Conclusions

The chapter introduces a conceptual framework to improve the design practices of microgrids with an emphasis on the techno-economic analysis component. The framework 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 framework comprises four modules based on the convergence of attributes towards sustainable remote microgrids. A focus group constituting the experts from academics, sustainability consultants, renewable energy practitioners, industrial experts and chairs of IEEE working groups, established the process to enable the practicability of the framework.

The practical framework provides essential information about renewable energy-based microgrid design and planning indices, such as the uniform access to electricity, designing for the users' energy needs, and their corresponding load patterns. Also, by integrating energy-efficient approaches, a well-managed decentralized system with better autonomy may be enabled. As investment is a vital factor responsible for the success of these kinds of 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 framework highlights significant features involving stakeholder engagements for project development and indicators focusing on the responsibilities and behavioral aspects of the microgrid developer and the users for prolonged electricity services.

The established practical framework, if utilized systematically, may contribute to improving the resilience of the communities where microgrids are deployed. However, practitioners will require a good understanding of methodologies from the sustainability sciences, such as transformative transdisciplinarity (van Breda 2019) and participatory approaches (Fouché & Brent 2020), which are integrated effectively in systems engineering practices, with an emphasis on the technical design and implementation of sustainable microgrids. This is the ongoing goal of, among others, the Sustainable Energy for All initiative of the United Nations (2020), and the Smart Village initiative of the IEEE (2020).

6. References

Akinyele, D., Belikov, J., & Levron, Y. (2018). Challenges of microgrids in remote communities: A STEEP model application. Energies, 11, 432. https:// doi:10.3390/en11020432

Bhattacharya, M., Paramati, S.R., Ozturk, I., & Bhattacharya, S. (2016). The effect of renewable energy consumption on economic growth: Evidence from top 38 countries. *Applied Energy*, 162, 733–741. https://doi.org/10.1016/j.apenergy.2015.10.104

Chandel, S.S., Shrivastva, R., Sharma, V., & Ramasamy, P. (2016). Overview of the initiatives in renewable energy sector under the national action plan on climate change in India. *Renewable and Sustainable Energy Reviews*, 54, 866–873. https://doi.org/10.1016/j.rser.2015.10.057

Chatterjee, A. (2020). *A Conceptual Framework to improve the design of sustainable off-grid microgrid systems for remote communities in developing countries*. PhD thesis, Victoria University of Wellington. http://hdl.handle.net/10063/8908

Chatterjee, A., Burmester, D., Brent, A.C., & Rayudu, R. (2019). Research Insights and Knowledge Headways for Developing Remote, Off-Grid Microgrids in Developing Countries. *Energies*, 2(10), 2008. https://doi.org/10.3390/en12102008

Chen, W.M., Kim, H., & Yamaguchi, H. (2014). Renewable energy in eastern Asia: Renewable energy policy review and comparative SWOT analysis for promoting renewable energy in Japan, South Korea, and Taiwan. *Energy Policy*, 74(C), 319-329. https://doi.org/10.1016/j.enpol.2014.08.019

EU Energy Initiative (EUEI). (2014). *Mini grid policy toolkit*. Retrieved October 28, 2020, from: http://www.minigridpolicytoolkit.euei-pdf.org

Fouché, E., & Brent, A.C. (2020). Explore, Design and Act for Sustainability: A participatory planning approach for local energy sustainability. *Sustainability*, 12, 862. https://doi.org/10.3390/su12030862

Gui, E.M., Diesendorf, M., & MacGill, I. (2017). Distributed energy infrastructure paradigm: Community microgrids in a new institutional economics context. *Renewable and Sustainable Energy Reviews*, 72, 1355–1365. https://doi.org/10.1016/j.rser.2016.10.047

Haghighat Mamaghani, A., Avella Escandon, S.A., Najafi, B., Shirazi, A., & Rinaldi, F. (2016). Techno-economic feasibility of photovoltaic, wind, diesel and hybrid electrification systems for off-grid rural electrification in Colombia. *Renewable Energy* ,97, 293–305. https://doi.org/10.1016/j.renene.2016.05.086

International Energy Agency (IEA). (2020). *Defining energy access: 2020 methodology*. Retrieved October 22, 2020, from: https://www.iea.org/articles/defining-energy-access-2020-methodology

International Electrotechnical Commission (IEC). (2015). *Recommendations for renewable energy and hybrid systems for rural electrification - Part 1: General introduction to IEC 62257 series and rural electrification*. IEC TS 62257-1:2015. Retrieved October 28, 2020, from: https://webstore.iec.ch/publication/23502

Institute of Electrical and Electronics Engineers. (2020). *Smart Village*. IEEE. https://smartvillage.ieee.org

Louie, H. (2018). *Off-grid electrical systems in developing countries*. Springer. https://doi.org/10.1007/978-3-319-91890-7

NASA. (2020). *Surface meteorology and solar energy database*. Retrieved October 27, 2020, from: https://eosweb.larc.nasa.gov

Palit, D., & Chaurey, A. (2011). Off-grid rural electrification experiences from South Asia: Status and best practices. *Energy for Sustainable Development*, 15(3), 266–276. https://doi.org/10.1016/j.esd.2011.07.004

Pepermans, G., Driesen, J., Haeseldonckx, D., Belmans, R., & D'haeseleer, W. (2005). Distributed generation: definition, benefits and issues. *Energy Policy*, 33(6), 787–798. https://doi.org/10.1016/j.enpol.2003.10.004

Roy, J., Dowd, A.-M., Muller, A., Pal, S., & Prata, N. (2012). Lifestyles, well-being and energy. In T.B. Johanson, A.A.P. Patwardhan, N. Nakićenović, & L. Gomez-Echeverri (Eds.), *Global Energy Assessment* (Chapter 21, pp. 1527-1548). Cambridge University Press. Retrieved October 27, 2020, from: https://iiasa.ac.at/web/home/research/Flagship-Projects/Global-Energy-Assessment/GEA_Chapter21_lifestyles_hires.pdf

Sawle, Y., Gupta, S.C., & Bohre, A.K. (2018). Review of hybrid renewable energy systems with comparative analysis of off-grid hybrid system. *Renewable and Sustainable Energy Reviews*, 81, 2217–2235. https://doi.org/10.1016/j.rser.2017.06.033

SESDC. (2020). *Working Group on Sustainable Energy Systems for Developing Communities*. IEEE. https://site.ieee.org/pes-sesdc/

Sinha, A., & Singh, J. (2011). Jamshedpur: Planning an Ideal Steel City in India. *Journal of Planning History*. 10(4), 263–281. https://doi.org/10.1177/1538513211420367

Troost, A.P., Musango, J.K., & Brent, A.C. (2018). Strategic investment to increase access to finance among mini-grid ESCOs: Perspectives from sub-Saharan Africa. *2nd International Conference on Green Energy and Applications (ICGEA)*. https://doi.org/ 10.1109/ICGEA.2018.8356268

United Nations. (2020). *Sustainable Energy for All*. UN. https://www.seforall.org

United Nations Development Programme (UNDP). (2020). *Sustainable Development Goals*. Retrieved October 22, 2020, from: http://www.undp.org/content/undp/en/home/sustainable-development-goals.html

van Breda, J. (2019). *Methodological agility in the Anthropocene: An emergent, transformative transdisciplinary research approach*. PhD thesis, Stellenbosch University. http://hdl.handle.net/10019.1/106959