Dynamic Life Cycle Sustainability Assessment of Mini-grids: A Proof-of-Concept

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Abstract:

As per the ‘World Energy Outlook 2022’ projections, 660 million people worldwide (mostly from rural areas) would be without electricity access in 2030. There are three main approaches to rural electrification - centralised grid extension, mini-grids, and solar home systems (SHS) including pico-solar. Mini-grids are considered a promising solution in rural areas with higher reliability (as compared to the central grid) and higher capacity to meet demand (as compared to the SHS). However, there have been failures of several mini-grid projects worldwide. There are various challenges faced by mini-grids – technical, social, economic, and strategic. The past efforts to assess mini-grid sustainability have used static approaches. Consideration of dynamic variations in the mini-grids over the life cycle for sustainability assessment is an emerging research area and is being explored in this paper. An attempt has been made to show how the dynamics and the interdependency of different aspects related to the mini-grids can be considered for life cycle sustainability assessment. Complex environments, local operations, many interacting variables, and feedback processes characterise mini-grids. ‘System dynamics’ is a systems method suitable to describe behaviours of such systems and tackle relevant problems. A system dynamics approach has been used in assessing an Indian mini-grid for a systemic understanding of its life cycle. The analysis reveals the impact of different variables on the mini-grid’s life cycle. Developed stock-flow (SF) diagram is useful for analysing different scenarios (e.g. arrival of centralised grid) and policies (e.g. tariff variations). This proof-of-concept (PoC) may help to develop a comprehensive framework for the dynamic life cycle sustainability assessment (D-LCSA) of mini-grids.

Keywords:

Mini-grids; System dynamics; Life cycle sustainability assessment; Proof-of-concept.

1. Introduction

1.1. Global electricity access

Electricity access has been a requisite part of any global development process. In the Sustainable development goals (SDGs) set by United Nations [1], SDG 7 is — Ensure access to affordable, reliable, sustainable, and modern energy for all. Particularly, SDG 7.1 aims at ‘universal access to modern energy’. Modern energy access also includes other types of energy carriers like cooking fuels and transportation fuels. But due to its strong linkage with the development, ‘electricity access’ is an area of interest for researchers, policymakers, and executors.

In India, on 30th April 1945, Mahatma Gandhiji wrote a letter to Cambridge return economist Shri.Amiya Nath Bose and expressed his concern about the electricity access to every home in India. He asked “Have you worked out the problem of electricity for every home? What is the cost?” [2]. In later years, various schemes for the extension of the electricity network in India, as well as at the global level improved electricity access but the challenges like network expansion, and poor financial returns on investment, remain for remote areas. Due to rapid urbanisation, more focus was on urban electrification and a majority of the rural population remained without any electricity access during the development stages.

As per the ‘World Energy Outlook 2022’ [3] projections, 660 million people worldwide would be without electricity access in 2030. The report [4] published to track the progress of SDG 7 mentions that rural electricity access is more deficient than in urban areas. In 2020, out of the world's population without electricity access, 80% of people lived in rural areas. Also at the current pace, the 2030 target for rural electrification will fall short. Figure 1 highlights the need for more focus on rural electrification in the next few years.

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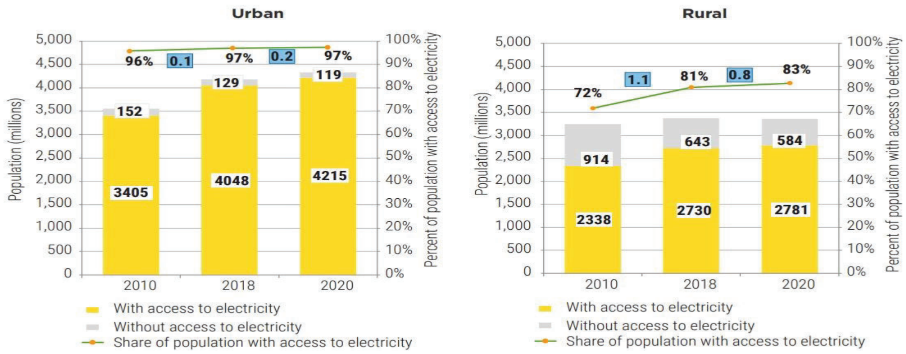


Figure. 1. Electricity access in urban and rural regions at the global level [4].

1.2. Approaches to rural electrification

Electricity access can be provided through three possible schemes/modes: - centralised electricity grid, mini-grids (or micro-grids), and solar home systems (SHS) including pico-solar. Off-grid electricity can be generated with more resources like diesel and biogas, but their share compared to solar electricity generation is much less. Moreover, the government schemes are more tilted towards "solar" due to the ease of installation, operation, and maintenance.

Centralised electricity supply is the conventional type of electricity supply scheme. This supply type is also called grid extension. The electricity is generated using various resources, such as fossil fuels (coal or NG-based plants), nuclear energy, and renewables e.g. water (hydropower plants), wind, or solar energy in centralised power plants. The same is transferred through the transmission and distribution network monitored by the national and state-level utilities. This is called the vertical structure of electricity supply. Until the technological advances started taking place in the renewable energy sector with the choice of decentralized electricity generation, the centralised supply scheme was the only option for providing electricity access.

The monopoly of the centralised supply scheme ended due to various reasons like increased competition in the electricity industry, entry of private players, technology development in renewable electricity generation, etc. There are various environmental, economic, technical, political, and social reasons for developing small-scale generation near the loads. This small-scale generation is called a decentralised electricity supply scheme. The systems can run in isolation (off-grid mode) or connected to the grid (grid-connected/online mode). The generation technology is either renewable (e.g. solar, wind) or non-renewable (diesel generator), or a combination of multiple technologies (hybrid mini-grids).

As discussed in [5], an SHS is usually defined as a solar PV-based generator rated 11 Wp to more than 100 Wp with suitable battery storage. The maximum PV module rating in an SHS kit is expected not to exceed 350 Wp as per the current standards. Products with rated PV power lesser than 11Wp are pico-solar.

Due to the various challenges like cost recovery and supply reliability for the central grid extension and the limitations of SHS and pico-solar ratings to fulfill the electricity demands, the rural areas find mini-grids as a promising solution. 'Ease of electrification vs. Power level' of various electrification modes is shown in Figure 2.

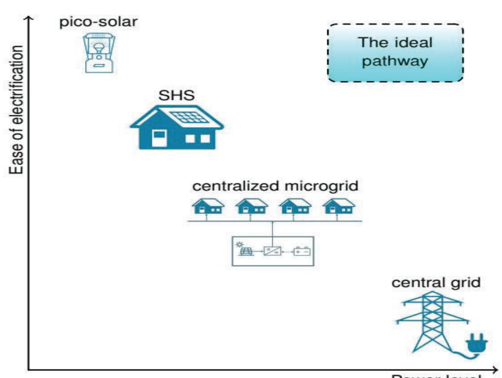


Figure. 2. Modes of electrification and comparison of ease of electrification vs. power level [5].

Delivery of electricity connections under the IEA Net Zero Emissions by 2050 Scenario, by technology, is shown in Figure 3.

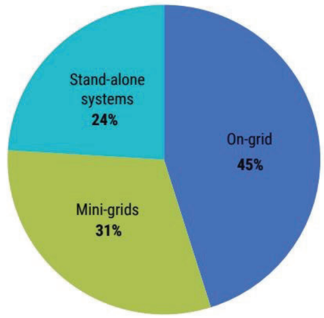


Figure. 3. Delivery of electricity connections by 2050 Scenario, by technology [4].

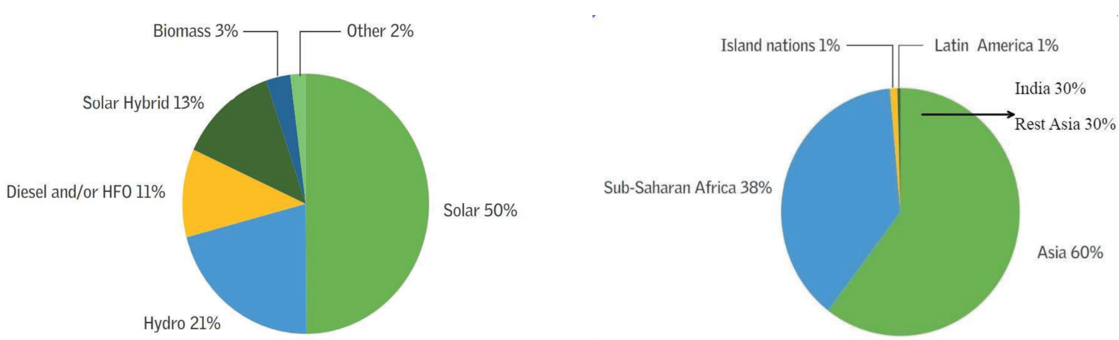
1.3. Mini-grids

1.3.1. Introduction

Mini-grids are off-grid systems but have provisions to connect with the grid and operate in parallel. They are local electric power networks with distributed generators, loads, and energy storage technologies. The term "mini-grid" is merged with "microgrid" in the literature though they have different generating capacities and a mini-grid has a higher capacity than a microgrid. A renewable energy-based mini-grid is defined in [6] as a system that uses a renewable energy-based generator (with a capacity of 10 kW or more) to supply electricity to a specific set of consumers (e.g. households and/or commercial, industrial, and/or institutional organizations) through a power distribution network. In this paper, the term "mini-grid" is used for off-grid AC electrical systems with solar PV as a source. Solar PV technology is more focused because of the maximum share as a mini-grid source as shown in Figure 4. A typical mini-grid consists of energy generation technology, battery energy storage, a power electronics converter, a power distribution system, and an energy management system (for metering and control purposes).

1.3.2. Global status and mini-grid scenarios

Plethora of literature discussing the technical aspects of mini-grids, their importance, and the challenges in mini-grids have been published. Their status in the global south and India are discussed in the reports [6,7] recently published by The Centre for Science and Environment (CSE). The status of the ten countries having best practices in mini-grid installations and the barriers to mini-grid installations and sustainable operations in India are explained in detail. There are 5,544 mini-grids deployed worldwide out of which 60 percent are present in Asia and 39 percent in Sub-Saharan Africa. India has 1,792 mini-grid installations, the highest in Asia. The status of mini-grid installations at the global level by technology and region is shown in Figure 4.



(a) (b)

Figure. 4. The global status of mini-grid installations: a) technology-wise, b) region-wise [6].

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Mini-grid case studies discussed in [6] may be classified as off-grid (e.g. Raimongol Kumirmari Island and Madavchandra Satjelia Island in Sundarbans, West Bengal), mini-grids with grid extension but poor grid services (Jargatoli and Basua Gumla, Jharkhand and Chanpatia in West Champaran of Bihar), mini-grid not operational due to grid arrival (Darewadi, Maharashtra and Dharnai, Bihar), grid-connected mini-grid (Odanthurai, Tamilnadu) and mini-grids with SHS (Chopan, Maharashtra).

1.3.3. Need for sustainability assessment of mini-grids

Life cycle sustainability assessment (LCSA) is a combination of three approaches of sustainability assessment- environmental life cycle assessment (E-LCA), life cycle costing (LCC), and social life cycle assessment (S-LCA). This is also called the triple bottom approach. Some more dimensions such as 'technical' or 'institutional' are also considered in the LCSA. A sustainability assessment of mini-grids is needed for various reasons. The literature having the notion of mini-grid sustainability is evolving since 2009. Mini-grids play a vital role in rural electricity access and their unsustainability will impact the sustainable development goal achievement.

Turkson et al. [8] infer that several global and national level policies and practices are envisioned to ensure sustainable energy generation. Boche et al. [9] discuss various barriers like lack of business consideration, the gap in strategic planning approach, and the neglect of social issues. It is also mentioned that overall microgrid sustainability consideration is still deficient at the global level.

The need for sustainability assessment is also understood from the field experiences of mini-grid projects. A mini-grid case study at a village called Darewadi from Khed Taluka (District Pune, Maharashtra, India) is discussed in [6]. This mini-grid was in operation since 2012. In 2019, the battery replacement was carried out. The centralised grid reached the village in 2021 but reliability and quality of supply are poor. Mini-grid could have been used in grid-connected mode but tariff regulations for the interconnection were absent. This case study highlights the failure of mini-grid projects after certain years of operation. The Dharnai mini-grid in Bihar state and the Barapitha mini-grid in Odissa state faced similar issues.

The rest of the paper is organised as follows. Section 2 describes the review of the sustainability assessment of mini-grids and highlights the research gaps. Section 3 introduces dynamics and systemic approaches in mini-grids. In section 4, the conceptual framework and proof-of-concept model are discussed. Section 5 simulates the model with the mini-grid case study in Maharashtra state. The results of the simulations are discussed in section 6.

2. Sustainability assessments of mini-grids

The literature was reviewed for "energy sustainability" and "electricity sustainability". The literature for "mini grid sustainability" was shortlisted from the above two sub-areas. A literature database platform "Scopus" was used for the literature review. The use of suitable keywords and the operators like "AND" and "OR" helped to review the literature systematically. Research gaps in the area of mini-grid sustainability are summarised in Table 1.

Table 1. Literature and research gaps.

Author/s	Research Gap
Turkson et al. [8]---------	Sustainability as a systems problem, Practical implications of the different sustainability dimensions, Systems thinking for explaining dynamic interactions and the long-term effects of different dimensions in detail. "Dynamic life cycle sustainability assessment" as the state-of-the-art method supports static analysis.
Boche et al. [9]-----------	Analysis of interdependence issues, Development of sustainability diagnosis tools, and systemic modeling of microgrids with short, medium, and long-term dynamics for causal linkages amongst various issues
Haase et al. [10]----------	Inclusions of more social indicators, the derivation of indicators, the consideration of methodical and input data uncertainties
Khatami -------------------- and Goharian [11]	An all-inclusive approach toward energy sustainability and a better framework for defining sustainability giving equal weightage to all dimensions and spatial considerations
Brent and Roger [12]---	An understanding related to the complexity of the socio-institutional systems
Ilskog [13]-----------------	An interdisciplinary approach to sustainability evaluation.
Lassio et al. [14]----------	More emphasis on the social dimension of sustainability is recommended.
Viegas et al.[15] ---------	Project and location-specific sustainability assessment methods for integrative and at the same time customized assessment

Author/s	Research Gap
Corona and San --------- Miguel [16]	The use of a dynamic approach for sustainability assessment temporal and spatial variation in the criteria (indicators).
Poudel et al. [17]---------	Internal and external factors influencing the sustainability of mini-grids, and linkages between the project attributes and sustainability dimensions
Katre et al. [18]-----------	Time-based sustainability studies capturing temporal variations.
Chatterjee et al. [19] ----	Microgrid definition, typology identification, standards revision, electrification planning, energy utilisation and planning, resiliency, system dynamics, and technology adoption and policy recommendations.

'Use of system thinking and system dynamics in sustainability assessment of mini-grids' is research gap as inferred by many authors. This paper explores the consideration of dynamics in the mini-grid life cycle for sustainability assessment. The next section discusses how the concept of dynamics is linked to mini-grids.

3. Dynamics in mini-grids

3.1. System thinking approach in mini-grids

Hartvigsson in his Ph.D. dissertation [20] discusses the systems thinking approach and its linkages with mini-grids. System thinking is a method for understanding interaction amongst variables and the resulting behaviour of the system. This is useful when systems are complex and influence the users at different levels. Systemic studies help to change the system structures which are the cause of certain behaviours. System thinking is divided into "soft" and "hard" system thinking. The "hard" approach is used in well-defined problems while the "soft" approach is useful when problems are "fuzzy", "messy" or "ill-defined". Mini-grids being complex and messy systems, the system thinking approach is useful for analysing mini-grids' behaviour. Some mini-grid problems can be engineered while others being societal are difficult to define. Thus mini-grids can be analysed with both "soft" and "hard" system thinking.

System dynamics (SD) is a dynamic thinking tool for qualitative (soft) and quantitative (hard) analysis which helps to understand the behaviour of the system over time. SD analysis consists of plotting behaviour over time (BOT) graph, development of causal loop diagram (CLD), and stock-flow (SF) analysis. Another characteristic of SD applicability is many feedback processes and interdependency among variables. The important literature in the area of SD applications to mini-grids is discussed in the next subsection.

3.2. System dynamics and mini-grids

SD conceptual modeling to tackle complexity in mini-grids is proposed in [21]. Variables and causal relations are either assumed or identified from literature and field visits. The paper develops CLDs for mini-grids but there is no discussion on part how they can be further used for the sustainability assessment of the mini-grids. Also, conceptual models like CLDs are often vague and ambiguous. Re-evaluation is needed by building SF diagrams. SF diagrams are useful for quantitative analysis and consideration of various scenarios. Riva et al. [22] develop CLDs for analysis of the impact of electricity access on rural-socio-economic development. Electricity- demand nexus with income generating activities (IGAs), local market production, households' economic availability, local health and population, education, habits, and social network is developed. This is a conceptual model development similar to the work published in [21]. Hence SF diagrams (simulation models) are required to validate the model. The authors also raise the need for reliable data collection from the field. Gonzalez et al. [23] construct CLDs using driving factors of social acceptance of renewable energy systems (RES). CLDs help to understand the multiple interactions of RES projects with rural communities. The sustainable livelihoods framework, created by the British Department for International Development (DFID) is used with system thinking qualitatively to understand RES acceptance. Though barriers to RES acceptance are discussed, their sensitivity to the project is not analysed through the SF diagram quantitatively.

Mini-grids behavior may be understood when their life cycle sustainability is analysed with system dynamics using simulations. To the best of the authors' knowledge, the research area is not much explored. The main contribution of this paper is proposing a PoC model for the "dynamic life cycle sustainability assessment (D-LCSA) of mini-grids".

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4. Materials and methods

In section 4.1, a conceptual framework depicting the system boundaries and various sustainability dimensions is discussed and a visual summary is provided in Figure 5. Then, section 4.2 illustrates a PoC model built according to the conceptual framework and focuses on system dynamic analysis. The PoC model is implemented in section 5 as a case study. The PoC addresses dynamics in mini-grids by connecting LCSA, mini-grids, and SD.

4.1. Conceptual framework for D-LCSA of mini-grids

Decision-making in sustainability assessment has the least or no influence on background processes while foreground processes are under the control of the decision-makers. In this paper, the sustainability assessment of operating mini-grids is considered. Hence the phases considered in the foreground system are the "use phase" and the "end of life phase". This is called as "Gate to Grave" approach in LCSA. The mini-grid system has physical exchanges (vertical arrows) for all phases in the form of input and output flows. These exchanges may be "elementary flows" (e.g. raw resources, emissions of pollutants and other materials into the environment, waste generated during the maintenance or at the end of the life cycle). The functional unit for LCSA is considered as 1 Unit (1 kWh) of electricity generated. A conceptual framework is shown in Figure 5.

For life cycle impact assessment, the conceptual framework considers the following two groups of variables: (i) variables in the mini-grid system (e.g. electricity generated, expenditure on maintenance, distribution losses) (ii) influencing variables in the socio-economic system (e.g. population, per capita income). These variables can be realised by different indicators like technical, economic, social, environmental, and institutional.

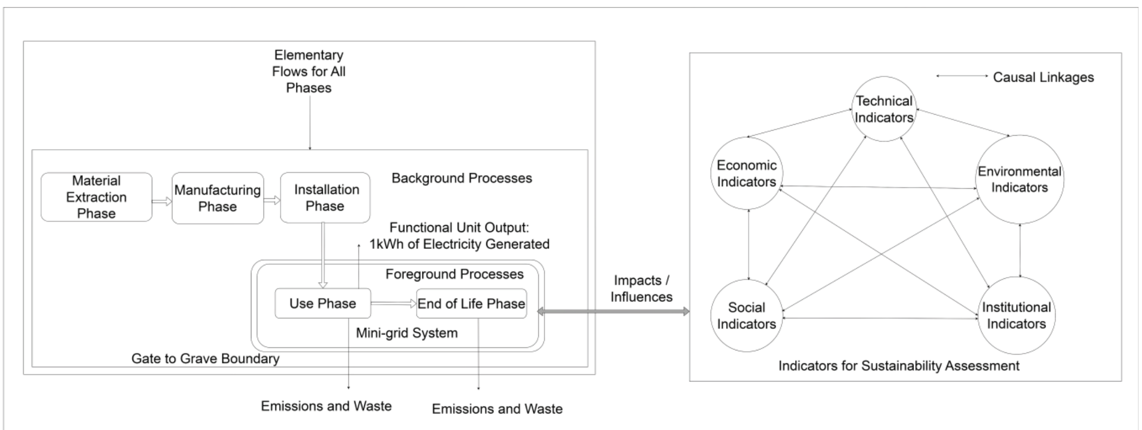

Figure. 5. Conceptual framework.

4.2. Proof-of- concept model for D-LCSA of mini-grids

Proof-of-concept model is developed to simulate "the dynamic impact assessment of mini-grid systems on livelihood and vice versa." Figure 6 represents the steps and all the elements considered in the model. Indicators used for LCSA of mini-grids are finalised by literature review and field visits for systemic understanding. The indicators are classified as technical, economic, social, environmental, and institutional. Cause-effect relationships amongst the indicators can be represented by CLD. Once the indicators are finalised, the next important step in the model is to develop the SF diagram. SF diagram requires two inputs: i) mathematical relationships amongst variables and ii) variables' values and changes with time. For the second input, a detailed questionnaire and interactions with the stakeholders are required. This activity will help with the local characterisation of mini-grid sustainability. Consideration of mini-grid location-specific data helps to model the local impacts and their consequences on the mini-grid system.

SF diagrams can be used to simulate the behavior of mini-grids. To compare the results from the analysis, it is required to decide the criteria for mini-grid sustainability. Literature review and initial fieldwork may help in deciding criteria. These criteria may be different for different stakeholders and thus need multi-criteria analysis. Inference on mini-grid sustainability can be drawn by comparing the simulation results with defined criteria. Scenario and policy analysis may help to minimize the sustainability gap. The next section discusses the development of the CLD and SF diagram for an Indian mini-grid case study.

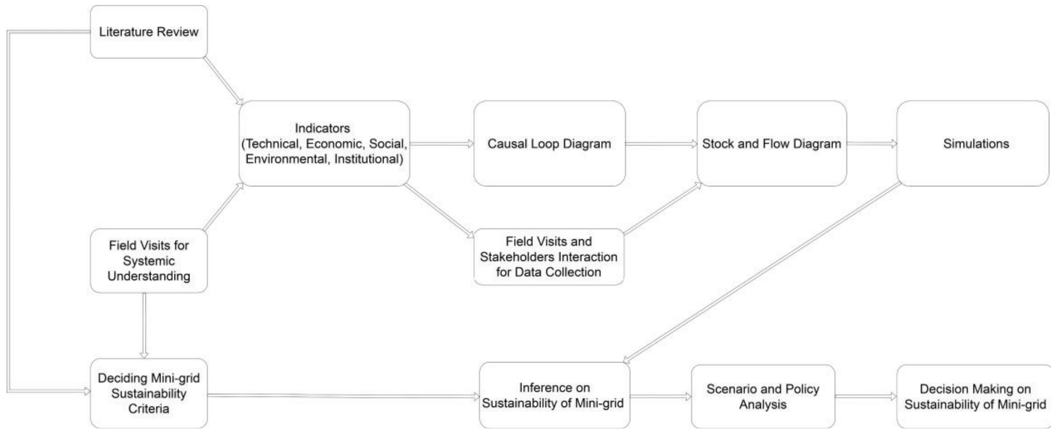

Figure. 6. Proof-of-concept model.

5. Case study

This section aims to develop CLD and SF diagram to assess mini-grid sustainability. The application of the PoC model is currently limited by the data availability for all the variables (indicators). In this paper, the development of CLDs and simulations of the behavior of a few indicators with SF diagrams are explored. Simulations show the variations in the mini-grid behavior with changes in the indicator values (assumed or collected during the field visit for systemic understanding). Comprehensive D-LCSA using all steps in the PoC model is envisaged after the survey questionnaire preparation and data collection from the field. CLD for a case study of a mini-grid at a place called "Makhla" is developed referring to [20-23] and modified as per interactions with stakeholders conducted for systemic understanding.

Makhla (Tembhurni Dhana) is a village in Chikhaldara taluka, Amravati district of Maharashtra state. The village is 104 km away from the district head quarter and is located in the Melghat tiger reserve forest. Electricity was not available in the village till October 2021 and the nearest centralised grid is 10 km away (Semadoh). 154 predominantly tribal families are residing in the village. Maharashtra Energy Development Agency (MEDA), a Government of Maharashtra institution has installed 37.8 kWp off-grid mini-grid in the village. Mini-grid was commissioned on 22nd October 2021. The basic energy requirement of the village is estimated at 200kWh/day. Energy storage of 110 kWh is supplied by 'amperehour solar technology Pvt. Ltd - energy storage solutions Company in Pune, Maharashtra, India. CLD for the Makhla mini-grid is shown in Figure 7.

In the developed CLD, the variables not bounded in any shape are referred from the literature. The variables in the solid box are the authors' contributions and in highlighted box are outcome of field interactions. In CLD, '+' sign represents the change in the variable in the same direction as the first. '-'sign represents the opposite change. Loops classified as reinforcing loops (R) and balancing loops (B) are marked in the CLD and listed in Table 2. Reinforcing loops create exponential growth while balancing loops create stability.

Table 2. Different loops in Makhla CLD.

Loop No.	Loop	Type
1	Mini-grid Income--Timely Repair and Maintenance--Battery Energy Storage Rating--Reliability of Electricity--Electricity Usage--Mini-grid Income	Reinforcing (R1)
2	Mini-grid Income--Timely Repair and Maintenance--Battery Energy Storage Rating--Reliability of Electricity--Social and cultural events--Conflicts between community and VEC--Mini-grid Income	Reinforcing (R2)
3	Mini-grid Income--Timely Repair and Maintenance--Battery Energy Storage Rating--Reliability of Electricity--Social and cultural events--Electricity Usage--Mini-grid Income	Reinforcing (R3)
4	Mini-grid Income--Timely Repair and Maintenance--Battery Energy Storage Rating--Reliability of Electricity--Electricity Usage--Cooking time--Health improvements--Satisfaction--Conflicts between community and VEC--Mini-grid Income	Reinforcing (R4)

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Loop No.	Loop	Type
5	Mini-grid Income--Timely Repair and Maintenance--Battery Energy Storage Rating--Reliability of Electricity—Electricity Usage--Safety from wild animals--Health improvements--Satisfaction--Conflicts between community and VEC--Mini-grid Income	Reinforcing (R5)
6	Electricity Usage--Working hours--Number of IGAs--Business Income--Investment in IGAs--Local economic opportunities--Local Employment--Per capita income-- New Appliances Purchase--Demand for electricity--Battery Energy Storage Rating--Reliability of Electricity--Electricity Usage	Reinforcing (R6)
7	Electricity Usage--Study time for students, Education level--Per capita income-- New Appliances Purchase--Demand for electricity--Battery Energy Storage Rating--Reliability of Electricity--Electricity Usage	Reinforcing (R7)
8	Battery Energy Storage Rating--Reliability of Electricity--Repairs and Maintenance Needed--Repair and Maintenance--Battery Energy Storage Rating	Balancing (B1)

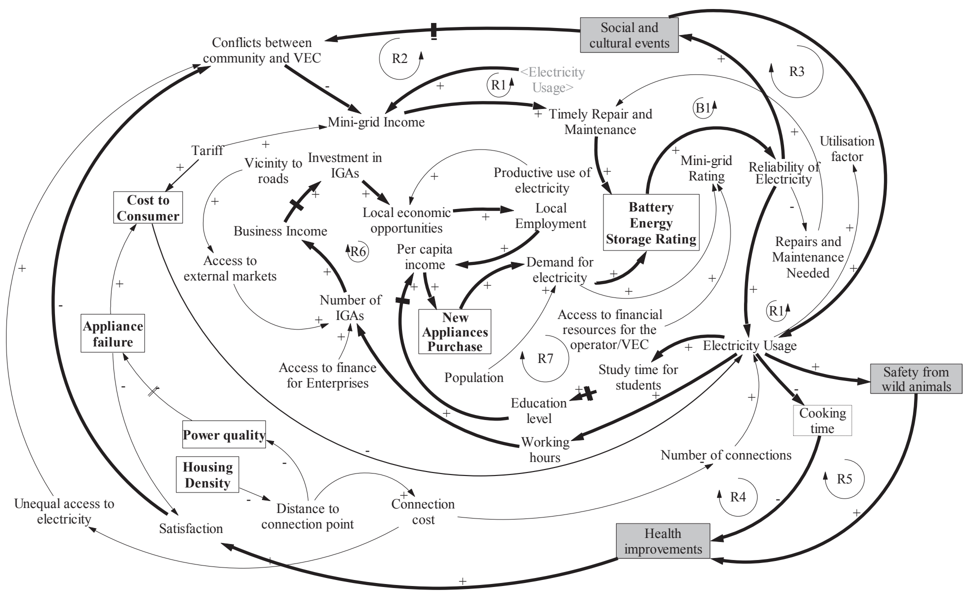

Figure. 7. CLD for Makhla mini-grid.

Mini-grid dynamics can be simulated using SF diagrams where stocks represent the accumulations in the system while flows represent the dynamics by defining how the stocks change with time. For SF analysis of the mini-grids, the identified stocks are mini-grid net income, battery capacity, electricity demand, electricity usage, and population. SF diagram for the Makhla mini-grid is shown in Figure 8. All variables from CLD, specifically qualitative ones are not included in the SF diagram as the aim is to show how quantitative analysis can be realised. Quantifying the qualitative variables is one of the challenges in the D-LCSA.

6. Results and discussions

In this section reinforcing loop R1 in Table 2 is simulated using Vensim software and results are explained in detail. Loop R1 consists of the variables: - “Mini-grid Income”, “Timely Repair and Maintenance”, “Battery Capacity”(Battery Energy Storage Rating), “Reliability of Electricity”, and “Electricity Usage”. “Mini-grid Income” is linked to “Timely Repair and Maintenance” by expressing later as the average delay in the process through a look-up table. The repair and maintenance are delayed due to lesser income which impacts the battery capacity. The relevant degrading factor is assumed. To calculate the “Reliability of Electricity”, it is necessary to understand the shortage of both battery energy and the power rating of the mini-grid system. For simplicity, faults or equipment failures are not considered. The “Reliability of Electricity” is linked to “Electricity Usage” through the sensitivity factor. Electricity usage will impact the mini-grid income and hence the loop is completed. The simulation results are shown in Figure 9 to Figure 12.

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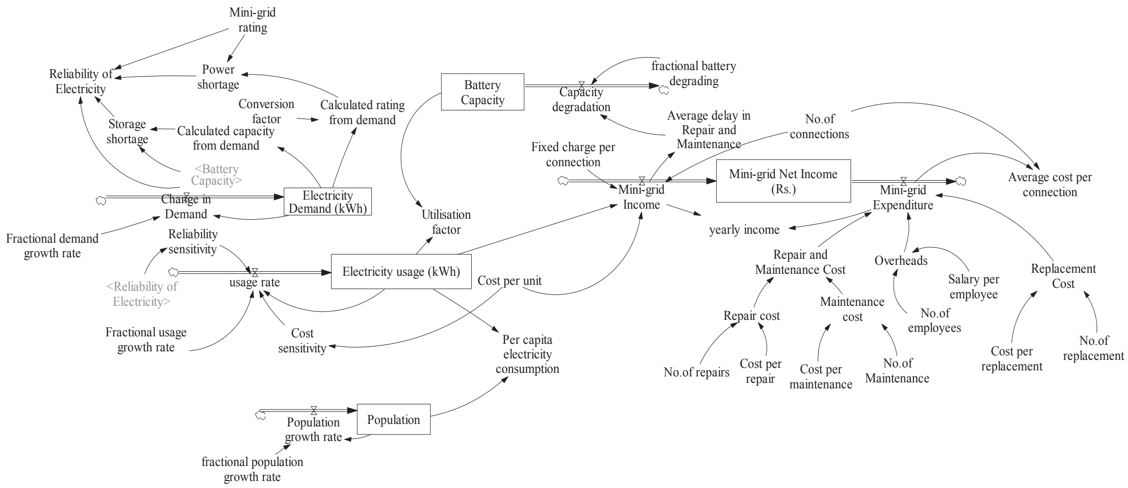

Figure. 8. SF diagram for Makhla mini-grid.

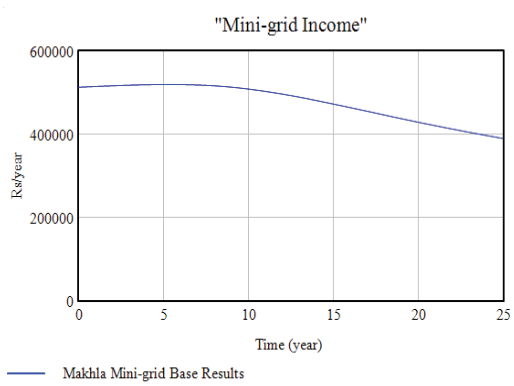

Figure. 9. Mini-grid Income.

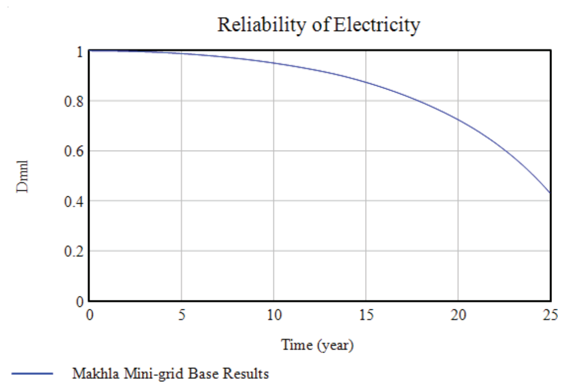

Figure. 10. Reliability of Electricity.

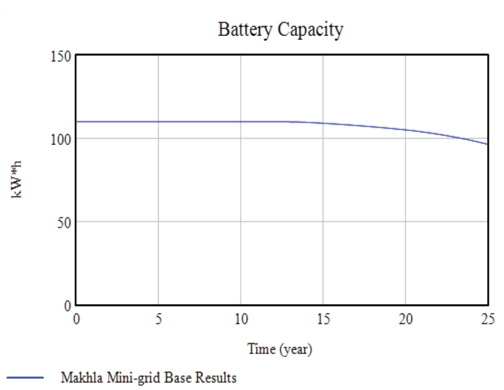

Figure. 11. Battery Capacity.

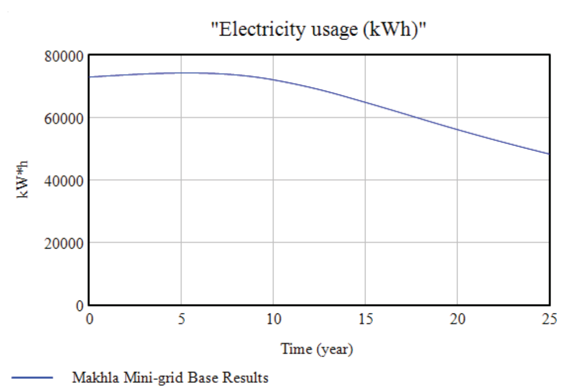

Figure. 12. Electricity Usage.

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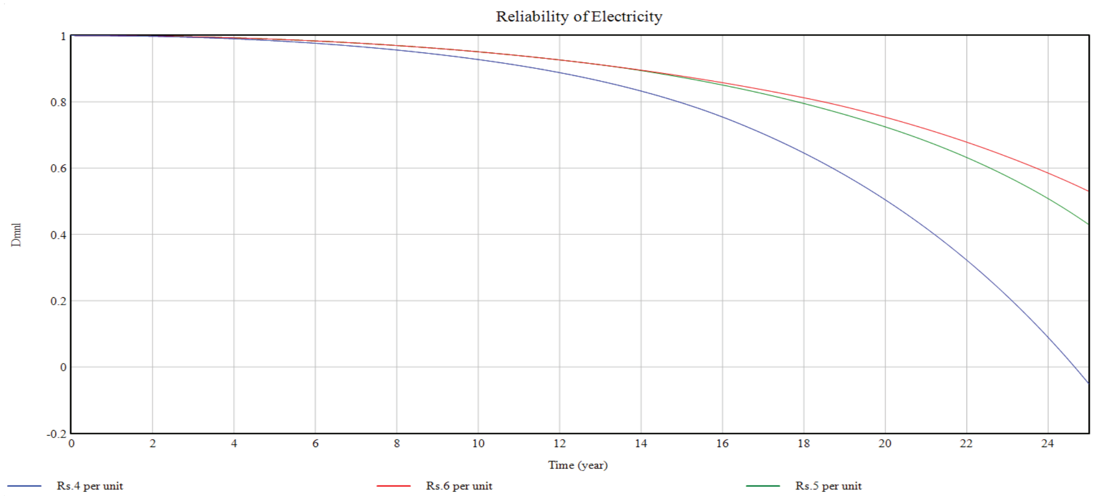

Figure. 13. Variations of Reliability of Electricity with Cost per Unit.

SF diagrams can be used for scenario analysis. The variation in the cost per unit (tariff) and its impact on reliability is shown in Figure 13. The existing tariff of Rs.5 per unit is first increased to Rs.6 per unit and then decreased to Rs.4 per unit for scenario analysis. Lower tariff results in higher usage decreasing reliability. Higher tariff reduces electricity usage and hence the reliability is higher. Similarly, the policies can also be analysed with the help of the SF diagram.

The inference for mini-grid sustainability can be drawn by comparing the simulation results with defined mini-grid sustainability criteria. The changes in the values of related variables may reduce or increase the gap in expected sustainability results. These analyses can be used as levers in decision-making related to mini-grid operations as shown in Figure 6. During the field visits, mini-grid systems are observed to follow some common patterns and face some common challenges irrespective of the location. These patterns may be modelled to generalise the performance of the mini-grid systems having similarities.

Conclusions

The framework presented in this paper attempts to conceptually identify limitations or scope of improvement in the LCSA of mini-grids. A proof-of-concept model was developed linking to dynamic causal relationships between technical, social, economic, environmental, and institutional variables to address life cycle changes in mini-grids. The important steps in models like the development of CLD, SF diagram, and simulation of the same are illustrated with a case study of a mini-grid in India. The results highlight the advantages of adding SD analysis into LCSA. The proposed model expands state-of-the-art impact assessment by incorporating dynamics. The results represent the behavior of the mini-grid systems by considering the complexity and non-linearity in the modeling. Developing the case study has highlighted the need for data monitoring for mini-grid systems. The accuracy of output depends on the availability of localised data. Future work could build on the research by use of the proposed model for comprehensive D-LCSA and developing a digital dashboard useful for all the stakeholders. Further applications of the D-LCSA model to case studies of various mini-grid scenarios may validate the proposed PoC model. “Defining mini-grid sustainability” is necessary to set the benchmark useful for sustainability analysis. The common and recurring patterns in the scenarios that shape the mini-grid behavior may be identified. Participatory SD not considered in the PoC can be explored for the formation of CLDs and quantify the feedback between different variables.

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