CONFERENCE ARTICLE

Navigating the Dynamics of Battery Operations in Off-grid Mini-grids: A Systems Approach

Omkar Buwa[1] | Anand B. Rao[1] | Jayendran Venkateswaran[2]

[1]Centre for Technology Alternatives for Rural Areas (C-TARA),
Indian Institute of Technology Bombay,
Mumbai, Maharashtra, 400076, India

[2]Industrial Engineering and Operations Research (IEOR),
Indian Institute of Technology Bombay,
Mumbai, Maharashtra, 400076, India

Correspondence
Omkar Buwa, Centre for Technology Alternatives for Rural Areas (C-TARA),
Indian Institute of Technology Bombay,
Mumbai, Maharashtra, 400076, India
Email: omkarphdwork@gmail.com

Off-grid mini-grid systems are considered a promising solution to unelectrified rural areas. Due to increasing environmental concerns, renewable-based mini-grids, especially with solar as a source, are installed in more numbers. The mini-grid ecosystem is complex due to the interconnected interactions of multiple building blocks and stakeholders. This complexity as well as the variations in the ecosystem over time of operational life bring sustainability challenges to mini-grid operations. The challenges may be classified as technical, economic, social, and institutional. Systems approach is suitable for the analysis of the sustainability of complex and dynamic systems. The dynamics of battery energy storage systems drive the technical performance of the mini-grids. To facilitate the sustainability assessment of mini-grids for rural electrification, this research aims to offer a causal loop framework for managing the dynamics of battery operations through a systems approach.

KEYWORDS
Off-grid mini-grids, Battery energy storage, Systems thinking, System dynamics, Sustainability

1 | INTRODUCTION

Sustainable Development Goal (SDG) 7 established by the United Nations (UN) aims to "Ensure access to affordable, reliable, sustainable and modern energy for all". As per The Sustainable Development Goals report, 2023 [1], at the current pace of electrification, 660 million people across the world will be without electricity access by 2030. The challenges of extending electricity are more in the rural areas and hence the urban-rural disparities in electricity access are observed. In 2021, out of the world's population without electricity access, 84% of people lived in rural areas. Also at the current pace, the 2030 target for rural electrification will fall short [2]. Hence there is a need for more focus on rural electrification in the next few years. Off-grid electricity solutions like mini-grids and solar home systems can help to reduce electricity disparities. At the global level, these solutions are being implemented through various schemes. A few examples of the schemes are the "Saubhagya" scheme [3] launched by the Government of India and the African Mini-grid Programme (AMP) by the United Nations Development Programme (UNDP) [4].

If the two off-grid electricity access solutions are compared, the mini-grids have the advantage over the solar home systems regarding more power capacity. Hence it is a promising solution at a village level where the main grid (national grid) electricity is yet to reach. In some cases, this is also seen as an alternative to the main grid due to better reliability. The number of globally installed and planned mini-grids, the investment, and the number of people connected shown in Table 1reflect the importance of the mini-grids in the electricity access program.

TABLE 1 Number of planned and installed mini-grids all over the world [5]

	No. of mini-grids	Cost in $ billion	People connected (million)
Existing (till September 2022)	21,500	29	48
Planned	29,400	35+	9
Requirement for universal access 2030	217,000	127	490

The report on mini-grids published by the Energy Sector Management Assistance Program (ESMAP) [5] states that half of the installed and ninety-nine percent of the planned mini-grids are 'solar-based'. There is no standard definition of the term 'mini-grid' and the terms 'microgrid' and 'mini-grid' are alternatively used in the literature. For all further discussions in this paper, a solar-based off-grid mini-grid is referred to as a mini-grid.

2 | SUSTAINABILITY OF THE OPERATIONAL MINI-GRIDS

Various challenges to the sustainability of mini-grids are discussed in [6], [7], [8] and [9]. All over the world, mini-grid project failures are experienced after a few years of commissioning due to various reasons categorized as technical, social, economic, and organizational (institutional). 156 such issues under various dimensions are identified in [10]. The term 'sustainability' is very broad and context-specific. For this research work, the sustainability definition for the mini-grids is adapted from the Ph.D. research work in [10]. The sustainability of mini-grids is defined as their ability to endure within the local context. This is very relevant to the need for the project and location-specific sustainability assessment methods raised by [11]. Furthermore, the definition has the following characteristics : (1) Internal operations vs. external considerations, (2) Established performance metrics, and (3) Local vs. distant external considerations. The stakeholders of mini-grids like investors, developers, operators, and end users are impacted due to the sustainability issues in the operational projects.

The sustainability assessment of mini-grids is an important exercise to understand their role in electricity access. As a routine practice, the techno-economic assessment methods for planning and performance assessment of the mini-grids are used which don't cover other sustainability dimensions. The sustainability of mini-grid operations is connected to various economic, social, and institutional factors. Existing mini-grid sustainability assessment frameworks focus more on impact assessment than the sustainability of the project. Moreover, these frameworks are project-specific, cross-sectional (static) rather than longitudinal (dynamic). Once the mini-grid is commissioned, there are a lot of changes occur at the system level during the operation due to complex interrelations between various dimensions. These interrelations and dynamics over the life cycle are not considered in the existing sustainability studies [12], [13].

3 | COMPLEXITY IN MINI-GRID ECOSYSTEMS AND SYSTEMS APPROACH

Mini-grid ecosystem means the building blocks of a mini-grid (solar panels, charge controller, battery system, inverters), electricity distribution system, end users, and other stakeholders like mini-grid developers, installers, and operators. The interconnected interactions amongst the building blocks and stakeholders make the mini-grid ecosystems very complex, as explained by [14]. The author refers to the definition of organized complexity to explain the complexity in the mini-grids. The behavior of a mini-grid ecosystem can be represented by the large number of variables that interact with each other. Hence mini-grids are organised complex systems. The context dependency where every actor has a different goal brings "messiness" to the mini-grid systems. Thus mini-grid ecosystem is characterized by complexity, many feedback processes, and high interdependency of variables. The systems approach is a useful method to solve issues in these systems.

Conceptual system dynamics (SD) modeling to tackle the complexity and uncertainties in mini-grids is developed by [15]. Understanding system description and defining the problem is discussed in detail. The complexity of mini-grids and the applicability of SD to solve issues in the mini-grids is highlighted. The paper developed CLDs for mini-grids which can be used as a basis for the systems approach in sustainability assessment of the mini-grids. The use of a dynamic approach in the sustainability assessment is discussed as the research gap by [16], [17], [18] and [19].

This work is part of the research objectives to develop a dynamic framework for the sustainability assessment of mini-grids using a systems approach. The paper focuses on the technical dimension of sustainability and the battery as a system component. Battery is very vital building block of the mini-grid. A causal loop diagram (CLD) highlighting the battery-related variables and their causal relationships with other sustainability dimensions is presented.

4 | BATTERY OPERATIONS AND THE SUSTAINABILITY OF MINI-GRIDS

Batteries are the heart of the mini-grid system. They account for more than one-third of the capital cost and need to be replaced timely to ensure the sustainability of the system [20]. The charging and discharging performance of the batteries decide the electrical energy received from the solar panels and sent to the load for demand fulfillment. Electricity demand and supply are the two important factors in the technical sustainability and hence the battery performance is strongly linked with the sustainability of the mini-grids. Figure 1 shows the developed CLD. The causal relationships are decided using the domain knowledge, referring to the literature, and discussing with the experts. Various causal loops showing the linkages of the battery operations to the other sustainability dimensions are discussed in the following subsections.

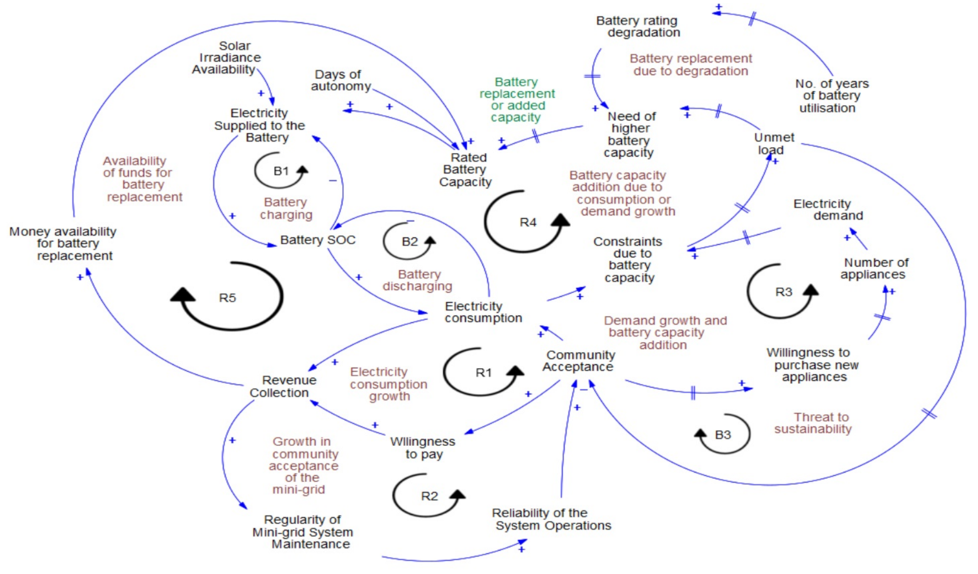

FIGURE 1 Causal loop diagram of battery operations and relevant loops

4.1 | Battery charging and discharging (Loops B1 and B2)

Battery capacity in the mini-grid is decided by various factors such as electricity demand (in kWh) and days of autonomy (days with no solar power generation). On a typical day, the amount of electricity sent to the battery from the solar panels depends on the solar irradiance at the location and the battery rating (capacity to store the energy). The battery will be charged to the rated capacity. The amount of electricity sent to the battery will decrease with the increase in the stored energy. The ratio of stored energy in the battery at any time to the rated capacity is called as state of charge (SOC). The system component of the mini-grid called the "charge controller" controls the battery charging level analogous to the water level controller. The charged battery once connected to the load starts sending energy to the load and the SOC of the battery decreases. The electricity consumption depends on the SOC as there are technical limits below which the battery is not allowed to be discharged.

4.2 | Electricity consumption growth (Loop R1) and community acceptance growth (Loop R2)

Electricity consumption generates revenue from the system with a pre-decided rate per unit of electricity. This revenue is vital for the proper maintenance of the system. The maintenance of the system is linked to the system's reliability and acceptance of the system by the community. This ultimately reinforces the electricity consumption. Improved community acceptance impacts the system operations in multiple ways. Other than increased consumption, the end users show their willingness to pay the bills on time increasing the revenue that otherwise would have been lost (assumption of ability to pay: the end users can pay the electricity charges).

4.3 | Electricity demand growth (Loop R3) and Battery capacity addition due to demand and consumption growth (Loop R4)

With the improved community acceptance, the number of electrical appliances increases adding demand to the system. With this increased demand and consumption, the existing battery capacity will not be sufficient and there will be a need for additional battery capacity. The total battery replacement may be required if utilised for a specific number of operational years. The reason is reduced capacity and health due to the degradation of the battery during the operational life.

4.4 | Availability of funds for battery replacement or capacity addition (Loop R5)

When the need for battery replacement or capacity addition occurs in the mini-grids (the reason may be consumption growth, load growth, or reduced capacity due to the degradation), the funds required must be available in the system account. The availability of these funds is ultimately ensured by healthy battery operations.

4.5 | Impact of unmet load on the sustainability of the system (Loop B3)

When the system is unable to serve the demand, the relevant load is called an unmet load. With frequent unmet load incidences, the system capacity may be considered short. If no action is taken on the issue, it may impact the community's acceptance negatively and further connected variables resulting in a threat to sustainable operations.

5 | CONCLUSIONS AND FUTURE WORK

The paper highlights the need and potential application of a systems approach for the sustainability assessment of operational mini-grids. As an example, the role of the battery operation in the sustainable operation of the mini-grids is explained through various loops. The CLD brings out various possible delays in the operational mini-grids. The analysis of these delays is also vital to ensure the sustainability of the system. Conceptual models like CLDs are often vague and ambiguous. The validity of the causal relationships is very important for more clarity. Moreover, re-evaluation is needed by building stock and flow (SF) diagrams. SF diagrams are useful for quantitative analysis and consideration of various scenarios. A better understanding of battery operations through modeling and simulations can help in maintaining the battery properly which will ensure the reliability of the system. Future work aims at validating the developed CLD through field discussions. The development of the SF model of battery dynamics in the mini-grids and validating the same using the field data is also planned.

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