Solar World Congress 2025

Applying Failure Mode and Effects Analysis (FMEA) to Community Solar Mini-Grids: A Proof of Concept

Summary

Community mini-grids are vital for rural electrification. However, many mini-grids fail due to technical, organizational, and social challenges, including a lack of local expertise and community involvement. Failure Modes and Effects Analysis (FMEA) is a structured method to identify and prioritize risks, traditionally focusing on technical failures. This work extends FMEA to a socio-technical approach, incorporating non-technical factors critical to the mini-grid's operational sustainability. Socio-technical FMEA involves diverse stakeholders to assess risks holistically through the participatory process. It captures interdependencies between technology, people, tasks, and governance. This approach enables targeted risk mitigation strategies beyond hardware issues. This proof-of-concept illustrates that socio-technical FMEA enhances the operational sustainability of community solar mini-grids and suggests future dynamic and criticality-based improvements for adaptive management.

Keywords: Community solar mini-grids, Operational sustainability, Socio-technical, Failure mode and effect analysis

1. Significance of community mini-grids for rural electrification

Sustainable Development Goal (SDG) 7.1 seeks to ensure universal access to affordable, reliable, and modern energy (electricity) by 2030 (United Nations, 2015). Current trends indicate that without increased focus and investment in rural electrification, the 2030 universal access target will not be met, highlighting the urgent need to accelerate efforts in decentralized renewable energy (DRE) solutions to bridge this gap (IEA, 2023). Focusing on renewable energy technologies, especially solar, there are two types of DRE systems: solar home systems (SHS) and "mini-grids" (also referred to as “microgrids” in the literature). Mini-grids have a better capacity to meet demand than SHS. Because of local energy storage, mini-grids are more reliable than the centralised grid and SHS. In rural, remote locations, mini-grids are considered a promising solution with higher reliability (compared to the central grid) and higher capacity to meet demand (compared to the SHS) (Palit & Bandyopadhyay, 2016). This work focuses on community solar mini-grids referred as ‘community mini-grids’ in further discussion.

2. Community mini-grid failures: causes and concerns

Several problems during the operations have led to the failure and abandonment of numerous community mini-grids. The failures are often rooted in a combination of technical, organizational, and social challenges. A primary cause is the lack of local maintenance expertise and insufficient community involvement, which leads to poor system upkeep and rapid abandonment of projects. Studies show that up to 60% of renewable mini-grid projects in some contexts are abandoned within just six months of installation (UNIDO, 2017).

Concerns also arise from inadequate alignment between the mini-grid capacity and the community's actual energy needs, often due to top-down approaches that exclude local voices in planning and governance (SEforALL, 2020; Aguirre et al., 2022). When community members are not consulted or trained, or when local authorities are not engaged, the solutions provided may not be accepted or utilized effectively, leading to a loss of trust (UNIDO, 2017; Global Climate Action Partnership, 2019). Without proper business models, reliable funding, and ongoing community engagement, community mini-grids struggle to deliver long-term benefits, highlighting the need for holistic approaches that prioritize local capacity building and responsive management (SEforALL, 2020; RMI, 2024).

3. Failure modes and effects analysis (FMEA): principles and processes

Failure Modes and Effects Analysis (FMEA) is a structured approach to anticipating and avoiding system failures. It helps stakeholders to examine all the ways the system might fail and the consequences that could follow. By understanding these risks early, improvements can be made to prevent failures, resulting in sustainable operations. The basic steps of FMEA include identifying possible failure modes, understanding their effects, and determining their causes. The Risk Priority Number (RPN) is calculated by multiplying the ratings for Severity (S), Occurrence (O), and Detection (D) which help in ranking the risks. By taking action to mitigate the risks and regularly reviewing the analysis, FMEA facilitates continuous quality improvement and helps prevent future failures. It's an essential tool for ensuring that systems function as intended (Stamatis, 2003; McDermott et al., 2009). Conventional FMEA typically focuses on technical components and processes.

4. Understanding community mini-grid failures through a socio-technical lens

The ‘socio-technical systems (STS)’ theory aids in understanding these failures. STS theory centers on four key components: the physical system (technology and tools), the task (work processes), the people (users and operators), and the structure (organizational roles and governance). Effective systems balance and integrate these components for sustainable operations. To grasp the failures, community mini-grids must be regarded as a system that goes "beyond the technical” (Agyekum et al., 2021).

Community mini-grids function as socio-technical systems where physical components like solar panels, batteries, inverters, and distribution networks collaborate with ‘tasks’ such as energy generation, maintenance, tariff collection, and supply-demand management. The ‘people’ subsystem includes community members who use, operate, and govern the system, while the ‘structure’ involves governance and institutional arrangements that define roles and communication among stakeholders. The operational sustainability of mini-grids depends on harmonizing these subsystems together to meet local energy needs effectively (State of the Global Mini-Grids Market Report, 2024; Leeds University Business School, 2025).

5. Applying FMEA beyond technical aspects in community mini-grids

Applying FMEA to community mini-grids beyond technical aspects involves incorporating all other subsystems alongside traditional physical systems (i.e. technical failure modes). This holistic approach helps identify failures related to stakeholder coordination, maintenance practices, economic sustainability, and policy compliance, which are critical for the operational sustainability of mini-grids. This research work proposes the application of ‘socio-technical FMEA’ to community mini-grids.

The socio-technical interactions and contextual factors unique to mini-grids can be explicitly considered in socio-technical FMEA. This enables more effective risk prioritization and mitigation strategies that address both technical and non-technical root causes, improving the resilience and operational sustainability of mini-grids. The interconnectedness of socio-technical dimensions in FMEA is addressed through its participatory, team-based process. This collaborative approach allows the team to factor in how technical failures may be influenced by, or have consequences for, people and structure. As a result, the RPN values implicitly capture these interdependencies making the risk assessment more holistic and reflective of real-world system operations.

Tab. 1: Illustrative example of socio-technical FMEA of community mini-grids

Socio-technical component (as per STS theory)	Example of failure mode	Severity (S)	Occurrence (O)	Detection (D)	RPN S x O x D	Brief Description
Physical system	Equipment breakdown	8	6	6	288	System fails due to component faults
People	Low community engagement	7	6	8	336	Lack of user involvement, misuse

Socio-technical component (as per STS theory)	Example of failure mode	Severity (S)	Occurrence (O)	Detection (D)	RPN S x O x D	Brief Description
Structure	Unsustainable business model	9	6	8	432	Revenue too low for maintenance

6. Conclusion and future directions

This proof-of-concept shows that a socio-technical FMEA provides a structured, participatory framework to identify and prioritize risks in community mini-grids by capturing their complex social and technical interactions. Future research could develop a dynamic socio-technical FMEA that updates risk assessments in real-time for more adaptive management. Integrating criticality analysis (FMECA) would further refine prioritization by considering the impact of failures, enabling better resource allocation for risk mitigation in complex socio-technical systems.

7. References

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