# Integrated Management Framework for Performance Challenges in Rural Off-Grid Microgrids: Addressing Deterioration in Electrification Systems

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# Integrated Management Framework for Performance Challenges in Rural Off-Grid Microgrids: Addressing Deterioration in Electrification Systems

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**Abstract**: Rural off-grid electrification systems have gained increasing attention, particularly in developing countries with vast rural areas. It is known that many established microgrids (MG) in rural areas are being challenged with a complex cost situation and numerous rural interferences, leading to various microgrid performance deteriorations, which are barely unchecked and lead to MG early failure. To address this issue, this study aims to develop a management framework to provide elaborate information and systematic analysis of the potential deterioration of rural off-grid microgrids. This study summarizes, identifies, categorizes, and addresses the challenges encountered in the rural off-grid MG and then highlights crucial issues that correlate to the potential deterioration. The challenges encountered in these MGs emphasize three key domains: financial, community, and technical. Financial challenges encompass funding continuity and item procurement, while community issues focus on the readiness of local operators and communication between stakeholders. Technical challenges include component deterioration and power system degradation. Notably, the findings highlight the connections amongst these domains, where unaddressed financial issues and uncommunicated community issues eventually impact the technical domain, thereby impairing power system performance. It is envisaged that the management framework of this research holds significant importance as it provides valuable insights for operators and managerial collaborators in tackling rural deterioration challenges during the operation of off-grid electrification.

Keywords: management framework; microgrid challenges; microgrid domains; microgrid performance deterioration; rural electrification system;

## 1. Introduction

Global research is moving together toward higher electrification ratios as much as possible every year[1)], aligning with the United Nations' goal of providing affordable, reliable, sustainable, and modern energy for all communities[2)]. This not only supports economic growth in the urban area but also reduces poverty in developing rural areas[3)]. However, despite its enormous benefits, rural electrification comes with unique rural challenges in both technical aspects and social aspects[4)]. Several microgrid projects face deterioration issues which lead to the early failure of the microgrid[5)].

Several studies point out a variety of reasons for off-grid system failure and underperformance, especially for rural microgrids, which are organizationally and technically more complex than household systems. Technical design is the main cause of microgrid deterioration. This begins with locally inappropriate microgrid design[6)], followed by poor component selection[7)], improper daily operations –mostly due to a lack of qualified operators[8)], and worn-out components resulting from missed maintenance schedules, often due to issues in project funding disbursement.

The root cause of the performance deterioration was undoubtedly pointed to the technical domain. However, aside from technical issues, previous research also points to several other issues, including financial issues related to maintenance budgets[9], community issues around insufficient participation and capacity building[10], lack of sensitivity and adaptability to local specificities, and unclear actor responsibilities[11]. It can be agreed with Marquardt[12] and Gollwitzer[13] that the debate on rural electrification has been dominated by technical challenges as much as social challenges. Furthermore, institutional and governance issues, including private-sector collaboration, require further attention. This highlights that the challenges in rural electrification are not solely come from a technical domain.

Contrary to most previous research[14][15][16] that discusses financial and community as a connected but distinct framework from technical, this research simultaneously addresses three critical domains –financial, community, and technical– in one management framework. This paper aims to develop a management framework that addresses the challenges faced by rural off-grid microgrids and provides an elaborate analysis of the potential deterioration on rural microgrid. The objectives of this study are to summarize, identify, categorize, and address the key challenges encountered in the rural off-grid MG and then emphasizes critical issues on the financial, community, and technical domains that correlate to the potential deterioration. By integrating these three critical domains into a single framework, this research offers a novel approach that goes beyond conventional discussions of financial and community aspects as separate from technical considerations.

The novelty of this paper lies in its holistic approach to the deterioration perspective, which simultaneously considers the connections of the microgrid domains. In other word, the significance of this work is:

1. This work introduces a management framework that is specifically designed to address the performance deterioration challenges in rural off-grid electrification systems, focusing on the identification and mitigation of multi-factor that can impact the system performance.
2. This study investigates a connection between domains of rural microgrids, which integrates financial, community, and technical domains, providing a comprehensive understanding of the challenges faced by rural microgrids and their interdependencies.
3. Limited previous research highlights the scarcity of studies addressing deterioration issues in rural microgrids, underscoring the importance of this study in filling this research gap.

## 2. Deterioration in Rural Electrification System

Rural electrification systems face the fact that a connection to the main utility grid comes with a high cost[17]. Mandelli *et al.*[14] corroborated this fact by comparing and classifying over 350 microgrid research projects from 2000 to 2014 and highlighting the role of small-scale generation systems in rural areas. Despite government incentives and well-developed policy frameworks[18][19], it is acknowledged that some centralized electrification programs provide services with subsidized rates far below cost recovery[17]. Therefore, an off-grid system arises as the best solution. Many researchers categorized the rural off-grid electrification system into four main sections[20]: generation, transmission, storage, and distribution. Figure 1 illustrates these four essential sections[3]: In a rural off-grid microgrid, the generation section mainly produces electricity from diesel generators (DG)[21][22]. Photovoltaics, commonly used in urban areas[23], comes as excellent renewable support for rural electrification systems[24]. The storage units help to deposit a sufficient amount of energy to stabilize the electricity supply, while the transmission line transmits the generated electricity from the generation section to the distribution network. At the end user, the distribution network delivers the transmitted electricity to the consumer.

Table 1. Investigation on rural hybrid microgrid system configuration and capacity

| Ref | Location | Configuration | Capacity |
|---|---|---|---|
| 25) | Senegal | PV, DG, Wn, Bat | 5 to 45 kW |
| 26) | Senegal | PV, Wn, Bat | ~40 kW |
| 27) | Bangladesh | PV, DG, Wn, Bat | 6 to 10 kW |
| 28) | Bangladesh | PV, DG, Bat | 2.4 to 5 kW |
| 29) | Cameroon | Wn, DG, Bat | 5 to 22 kW |
| 30)31) | India | PV, DG, Bat | 4 to 50 kW |
| 32)33) | India | PV, Wn, Bat | 5 to 50 kW |
| 34) | Iran | PV, DG, Wn, Bat | 1 to 5 kW |
| 35) | Argentina | PV, DG, Bat | 1 to 6 kW |
| 36) | Jordania | PV, DG, Bat | 2 to 4 kW |
| 37)38) | Africa region | PV, DG | 3.7 to 35 kW |
| 39) | Malaysia | PV, Bio, Bat | 0.3 to 1 MW |
| 40) | Algeria | PV, Wn, DG, Bat | 1 to 80 kW |
| 41)42) | Palestine | PV, DG, Bat | 5 to 14 kW |
| 43) | Philippines | PV, DG, Bat | 1 to 3 kW |
| 44) | Peru | PV, Wn | ~1 kW |

*PV: Photovoltaic, DG: Diesel Generator, Wn: Wind Power, MH: Micro Hydro, Bio: Bioenergy, Bat: Battery*

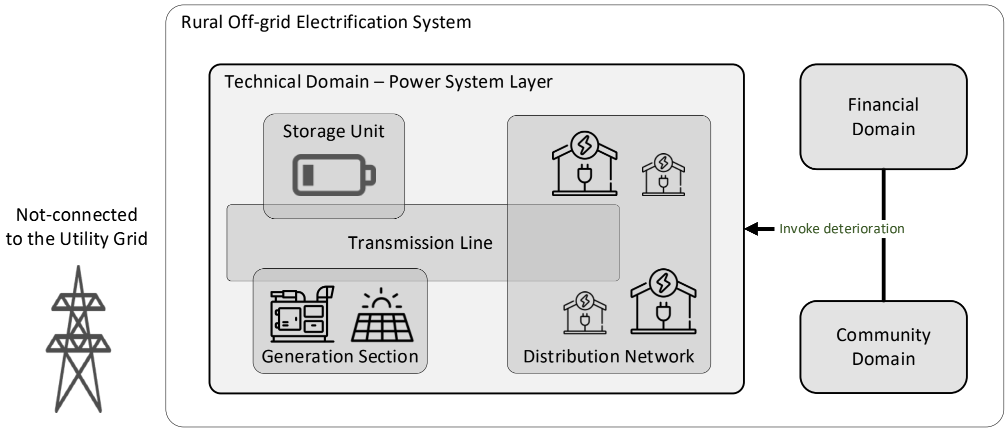


**Fig. 1:** Microgrid sections in rural off-grid electrification system.

### 2.1 Defining the parameter of rural off-grid electrification

This subsection delineates the scope of rural microgrids discussed in this study, providing insights into their key parameters and characteristics. The implementation of rural off-grid microgrids is comprehensively summarized in Table 1, which encompasses the location, energy source, and capacity aspects. Table 1 excludes non-rural microgrids and non-hybrid microgrids to focus exclusively on rural off-grid hybrid microgrids. Notably, a predominant configuration observed in these microgrids is the PV-DG-Bat setup, where photovoltaic (PV) panels are combined with diesel generators (DG) and battery storage (Bat). Hence, the framework proposed in this work is specifically tailored to address the challenges and deterioration issues associated with the PV DG Battery microgrid configuration. It is worth highlighting that the capacity of rural off-grid microgrids typically ranges from 1 to 15 kW on average, reflecting the power requirements of rural areas.

### 2.2 Microgrid sections with potential deterioration

The deterioration was not only because of worn-out components or aging microgrid module [45] but also because of the influence of funding issues on the operational and socio-technical barrier within the surrounding microgrid communities [46]. Each section was found to have the potential for deterioration, which can reduce microgrid performance and lead to failure. In addition, a bibliometric analysis using the Scopus database has been conducted to further support the uniqueness of the framework in this study. Out of 1,111 publications discussing "microgrid management framework" from the last decade (2014-2023), only 34 publications focused specifically on rural areas, and none of them addressed the identification of deterioration challenges. This bibliometric analysis highlights the scarcity of research on deterioration issues in rural microgrids and underscores the significance of the work in addressing deterioration impact. It is highlighted that this paper focused on the deterioration scenario, which reduced the rural off-grid microgrid performance. Any alternative scenario which improves the microgrid performance was not discussed in detail and shall be attended to in further study. Further action needed to reduce or repair the deterioration shall also be discussed in another detailed future research.

### 2.3 Deterioration framework approach and constrain

To develop the microgrid management framework and address the deterioration challenges in rural off-grid systems, a comprehensive research approach was adopted. The methodology focused specifically on rural areas in developing countries and was limited to PV-DG (Photovoltaic-Diesel Generator) rural microgrid systems [15]. The data collection process involved a systematic review of previously published research, case studies, and relevant literature specifically related to rural electrification in developing countries and the utilization of PV-DG systems. Qualitative data were derived from various sources, including academic papers, reports, and case studies that specifically addressed the implementation and operation of PV-DG microgrid systems in rural areas of developing countries. These sources offered valuable information on the financial, community, and technical challenges specific to certain geographical settings. The collected qualitative data were then systematically analyzed to identify recurring issues and patterns related to the deterioration challenges in PV-DG rural microgrid systems in developing countries [47]. The microgrid management framework was developed based on findings from the literature review and case studies conducted within the defined geographical context. This framework provides a structured approach for addressing and mitigating the identified challenges specific to PV-DG rural microgrid systems in developing countries. It is important to note that the limitations of this study include its focus on rural areas in developing countries and the specific use of PV-DG systems. Consequently, the findings and recommendations of this research are intended to be applicable within this defined geographical and technological scope.

## 3. Deterioration Challenges in Rural Off-grid Microgrid Systems

The power system domain is indeed the core of the microgrid. It contains every operational peripheral from the energy source to the user's device. However, other domains simultaneously operate along with the power system. According to[20] and[46], the financial domain and the community domain were indirectly affecting the technical domain.

### 3.1 Deterioration challenges distribution across domains in rural off-grid microgrid

Table 2 provides insight into how the microgrid challenges should be divided into principal domains. Figure 2 introduces a visual representation of how the financial domain and community domain affect the technical domain. In the financial domain of microgrid projects, critical challenges include appropriate initial design, efficient funding disbursement for daily operations, and timely maintenance. These factors significantly influence the grid's effectiveness, service quality, and component longevity. Community engagement is equally crucial. The capability of local operators, stakeholders' involvement, and policymakers' awareness all impact the microgrid's efficiency and success. As collaborators and policymakers may not be located close to the project, their interests and decisions can nevertheless profoundly affect its operation. Lastly, in the technical domain, the deterioration of both power system layers and components poses a threat to the expected energy capacity and overall lifespan of the microgrid. Aging or worn-out components and transmission losses can lead to performance degradation, underscoring the need for robust design and maintenance strategies. It is also acknowledged that anything that happens in financial and community aspects shall potentially stir up the degradation of technical aspects and lead to the deterioration of the rural off-grid microgrid performance.

### 3.2 Financial challenges on rural off-grid microgrid

The quality of the microgrid output is often tied to the operational cost. Both daily operational and routine maintenance depend on how much the amount of funding available. The daily operation consists of continuous functions which must be followed with assured spare part availability, while the routine maintenance involves the periodical activity to maintain the microgrid performance always at the optimum threshold. Limitations to the project budget brought a limited capacity for operation and maintenance[48], whereas it is absolutely demanded that microgrid components should be always-available as a whole to avoid any section dysfunction or blackout[49]. Even further, the quality of the grid also requires regular upgrades[50]. Therefore, the continuation of the project funding is discussed in the next section. Prior to the operation and maintenance, project funding affects the microgrid even earlier at the stage of technical design. Technical designs hold significant importance and must unavoidably meet the standard of power quality[51]. Insufficient capital funding can potentially lead to a suboptimal microgrid design and is frequently followed by the selection of inadequate microgrid components[52]. Therefore, financial challenges should be addressed from the early start of the microgrid project, including the community selection process.

Table 2. Domains of the microgrid challenge with potential deterioration of rural electrification system

| Main Domain Challenge | Sub-Domain Challenge | Critical Challenge |
|---|---|---|
| Financial Domain [48][49][50][52] | Initial Design | Microgrid design defines the quality of the microgrid and follows up the selection of the microgrid component. |
| | Daily Operation | Daily operation demands a fast and sufficient funding disbursement. |
| | Routine Maintenance | Missing the funding or delayed funding could postpone the scheduled maintenance and deteriorate component function. |
| Community Domain [53][54][55][56] | Operators Capability | Operators are the limited number of people located at the site or close to the microgrid site. |
| | Stakeholders Involvement | The collaborators are usually not in close proximity to the microgrid but have quite extensive connections and interest in the microgrid service. |
| | Policy Makers Awareness | Some parties do not literally connect to the microgrid project, but their authority affects the microgrid operation. |
| Technical Domain [7][58][60] | Power System Layer deterioration issue | Many factors can raise the failure to produce the expected energy capacity. Moreover, the transmission could also elevate the losses. Storage degradation and unstable distribution network could also decrease the microgrid performance. |
| | Component Layer deterioration issue | Aging components or wear-out components of the microgrid would introduce errors that invoke a faster time to failure and a shorter expected lifetime. |

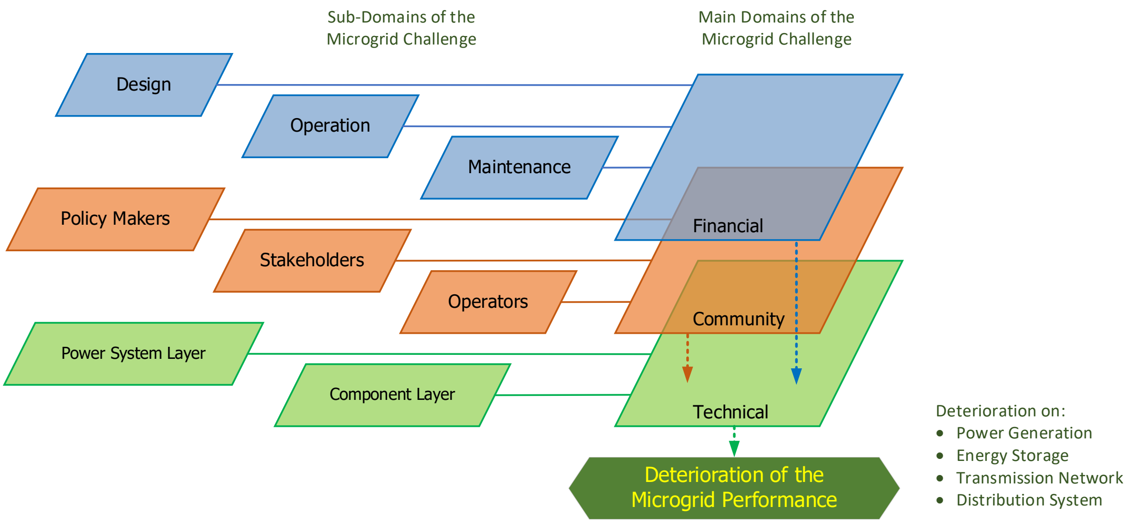


**Fig. 2:** Distribution of the challenges on the microgrid deterioration in rural electrification system.

### 3.3 Community challenges on rural off-grid microgrid

In the context of this study, the term "community" refers to the collective group of operators, stakeholders, and policymakers involved in the rural off-grid microgrid project. The surrounding communities play a crucial role in directing the operational line of the microgrid. From the beginning of the installation until the present operation and maintenance, the communities define whether the microgrid is running or on hold[53]. Operators, stakeholders, and policymakers are considered as the three sub-domains of the community domain in this work. The local operators who operate within the electrification area is the first community to determine day-to-day management. It is highly required that operator have sufficient skill and adequate workforce to manage and maintain the system [54]. While the government is often the primary source of funding[55], involvement from donors and investors is highly needed to provide capital and interest[56]. On the strategic level, the government, as policymakers, establishes a subsidy regulation that create an environment conducive for potential collaborators to join the project[57]. On the other hand, stakeholders ensure the quality of every stage of the project, including a good quality microgrid design, market research, and good quality components. It is acknowledged that stakeholders also determine the business process of the microgrid project, overseeing daily operation and routine maintenance.

### 3.4 Technical challenges on rural off-grid microgrid

The performance of the microgrid is ultimately determined by its technical section. As the power system always plays a central role, the other layer inevitably impacts the microgrid performance parameters. There are numerous other layers beneath the power system[58]; for example, the storage unit and transmission line, which may deteriorate due to corrosion[59]. However, it can be concluded that the most significant layer affecting the microgrid is the component layer[58]. While the power system handles the electrification flow, the component layer defines the electrification quality. It is crucial to ensure that all the components of the microgrid consistently fulfill the standards for power quality[51]. The power system layer mainly covers the generation section, transmission line, and distribution network, with an additional storage unit. These layers present complex challenges as each section affects one other[60]. The component layer highlights the potential deterioration which is caused by the quality of the component. The wear-out component or the aging component usually defines the probability of microgrid survival during the operating time[7].

## 4. Microgrid Management Framework to Address Deterioration Challenges

The present framework is designed to enable the microgrid operator to address the deterioration challenges outlined in the previous section. Each challenge develops a certain issue that practically induces a deterioration in the microgrid performance. Unaddressed issues were followed by numerous potential impacts which are related to each other, accelerating the deterioration process. The framework at the hand of the operator should anticipate potential deterioration or, at least, decelerate the deterioration speed on the microgrid performance.

### 4.1 Emerging issues in financial domain

Funding issues normally revolve around budget allocation and the ease of fund disbursement. The contractor and consultant rely on the initial capital funding to install such a proper microgrid that adheres to appropriate standards[51]. It is highlighted that inadequate capital funding initially results in poor-quality design and suboptimal component selection[14]. Market research is one crucial research in developing an appropriate microgrid for specific rural areas. However, when it came to funding for market research, it was either infrequently addressed or even more was missing[61]. Aside from the initial capital, the mid-year budget cutting is also a common cause of disrupting the operation of the microgrid. Budget cutting assuredly reforms the daily operational cost and rearranges most of the scheduled maintenance[19]. This disorganized trend can escalate and become unmanageable, thus difficult to mitigate. Ultimately, it stimulates a worn-out component which leads to system deterioration.

The cost and availability of quality items pose another challenge in rural areas. The price for good quality items is inappropriately high for rural areas, and their availability is considered low[17]. Not only the main part but the replacement component was also similarly difficult to find, including items like battery cells, circuit breakers, inverters, and converters[54]. In daily operation at the generation section, acquiring gasoline for diesel generators can be time-consuming, even with enough financial capability. This is because rural areas are sometimes geographically isolated, with terrain and distance adding to the logistical complexity[62]. Conversely, operators with a lack of financial capability frequently meet slow funding disbursement, prematurely raising a wear-out issue on the technical layer. It can be inferred that budgetary constraints had an impact on the under quality design, disrupted microgrid operation, and rescheduled maintenance[48]. Additionally, when the failed component emerges with rare availability, limited funding compels the operator and the contractor to immediately take the least expensive option and focus on the number, prioritizing quantity over quality.

### 4.2 Emerging issues in community domain

Microgrid operators and collaborators were considered as the actors in the field that would see how much the deterioration and what to do about it. Operators are the people who work and reside in the vicinity of the microgrid, spanning the generation to the distribution network. In the early stage, it is required that the operator and the contractor have enough-depth consideration in designing and planning the microgrid architecture[54]. Inadequate knowledge of the big picture often results in designs that are overly optimistic about one sector while failing to anticipate problems in other sectors. This inadequacy led to microgrid deterioration, especially in the sector that was not well anticipated[8].

In the operational stage, the rural area brings out the issue of a limited number of skilled workforces. People with good skills usually went to the urban area and left the rural area with potential people with a lack of technical skills. If the project is not adequately funded, there may be limited opportunities for training[54]. Smaller workforce has also demanded to handle a multitasking job. If this is not immediately addressed, it will be followed by an unclear job description and less commitment to the job. This challenging circumstance led to inadequate task completion and poor supervision[54,63]. Collaborators are those who were indirectly connected to the microgrid but were relatively related to the microgrid operation. Those who are relatively distant from the microgrid are encouraged to engage with operators and local residents to support the operation of the microgrid and share the resultant revenues and costs[53]. They, including donors and investors, should be involved[56] to support the government as the primary funding benefactor. The absence of these collaborators makes funding availability and capacity unreliable due to the inherent limitations of government funding.

At the strategic level, the government needs to act as the main funding provider and policymaker, formulating subsidies to support rural microgrids. Without subsidy, the high price of the materials and the low availability of good-quality items will be unattended, leading to the inevitable microgrid deterioration. Community issues brought out more pervasive impacts than financial issues, spreading into other unpredicted domains. In the operator issues, the lack of skill and rare training opportunities negatively impact microgrid maintenance which directly contributes to microgrid failure[54]. In terms of top management issues, the unsupportive policies prevent the donors and the investor from laying the contract and leave the local institutions as the only actors. A sudden policy change in the middle of the project can lead to the discontinued contract, leaving the microgrid unattended.

In a larger-scale energy project, rural microgrids usually face a shortage of trained human resources, ambiguous local regulations, and unclear coordination among local institutions, which affect the financing mechanism. The rural area usually has unique communication issues due to limited facilities and unequal statuses[64]. This communication issue invokes an entrenchment of social hierarchy, and segregation in each role brings the microgrid unattended. For example, a microgrid project deployed and donated by the government and interested parties loses its continuity because of a lack of communication among the role players. This scenario was named the “Drop and Go” scenario and raised a question of the microgrid ownership. It can be concluded that communication issue between communities should be attended to avoid the Drop and Go scheme. In the end, priority should be given to projects where the initiative comes from the local community.

### 4.3 Emerging issues in technical domain

Power system issues commonly start with the deterioration of the generation section. Even though the energy source is sufficient enough, the quality of design, architecture, or component can trigger an inadequacy of generated power capacity. Constraints on the transmission line are also found in several ways, which stimulate in the form of loss of transmitted power and later affect the user end electricity demand. Storage installation helps a lot in providing stabilized generated power and compensating the loss in the transmission line; however, the erroneous selection of the type and material shall potentially reduce the storage efficiency[65], decrease the capacity[66], and reduce the life cycle[67]. Microgrid issues on the component level shall be initiated by a prolonged period of operation, irrevocably caused by the late lifetime of its component, or because of a poor choice in the component procurement[7]. The latter has occurred in correspondence with the unmanageable funding scheme. The long-term operation will supposedly wear out the output quality. The aging component will cause a degradation of component materials and trigger a potentially unstable output. The next issue in the component domain revolves around the poor-quality item, which is usually procured due to the lack of technical understanding. These items will disrupt the whole system, becoming unfit for function and formation, and lead to the failure of the microgrid[54]. These issues commonly arise because of the shallow technical understanding or inadequate knowledge of the operator's workforce. These issues should be addressed by compelling sufficient funding to carry out training or recruitment of proper community members.

It can be concluded that the issues that occurred in the component layer directly impacted the performance of the microgrid. There are several indicators of microgrid deterioration. Firstly, the loss of load can be measured by loss of load probability (LOLP), loss of load expectation (LOLE), or distorted grid[68]. Secondly, deterioration in power generation can be measured using the occurrence of expected energy not produced (EENP)[69]. Lastly, the deterioration of the storage unit can be monitored at the degradation of the battery's SOC[67]. It is highlighted that the poor-quality component can lead to a shortened microgrid expected lifetime and a quicker time to microgrid failure.

### 4.4 Synthesis of emerging issues and mitigation framework

Given the complexity of the issues identified in the preceding sections, this paper puts forth a comprehensive management framework designed to address the issues surrounding deterioration within rural off-grid microgrids. The primary objective of this framework is to serve as a decision-making tool that enables proactive identification, assessment, and mitigation of potential deterioration factors within microgrid management. The framework is more than just a theoretical model; it is a pragmatic guidance that empowers the community to work in unison to identify deteriorations. With such collaborative efforts, the framework aims to ensure the microgrid's sustainable operation and, in turn, positively contribute to rural electrification.

Figure 3 serves as a visual aid by presenting a doughnut chart that categorizes the distribution of issues and challenges across multiple domain and subdomain of rural off-grid microgrids. This graphical representation was selected for its capacity to categorize and quantify

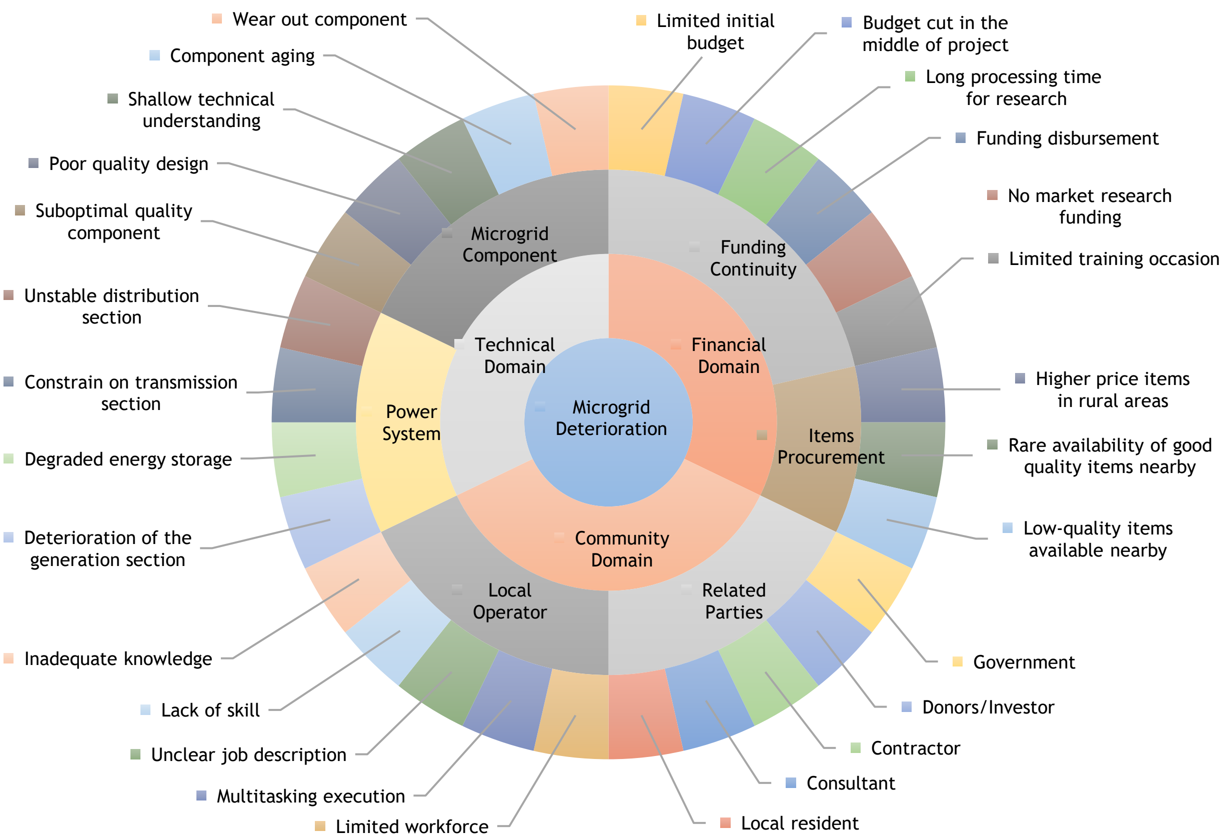


**Fig. 3:** Doughnut chart of emerging issues and challenges in rural microgrid domains.

Table 3. Breakdown of the emerging issues and the impact of the potential deterioration on the rural electrification system

| **Emerging Issues in Each Domain** | | **Potential Impacts** |
|---|---|---|
| **Financial** | | |
| Funding continuity [14)61)] | Limited initial budget<br>Budget cut in the middle of the fiscal year<br>Long processing time for research<br>Funding disbursement<br>No market research funding<br>Limited training occasion | Cheapest price selection<br>The limited budget for operational & maintenance<br>Focus on number; quantity above quality |
| Items Procurement [17)54)] | Higher price items in rural areas<br>Rare availability of good quality items nearby<br>Low-quality items available nearby | |
| **Community** | | |
| Related Parties [53)56)] | Government<br>Donors/investor<br>Contractor<br>Consultant<br>Local resident | Limited communication because of inequality status<br>Unsupportive policies<br>Discontinued contract<br>Drop and Go - the question of ownership |
| Local Operator [8)54)] | Limited workforce<br>Multitasking execution<br>Unclear job description<br>Lack of skill<br>Inadequate knowledge | |
| **Technical** | | |
| Power System [60)67)] | Deterioration of the generation section<br>Degraded energy storage<br>Constrain on transmission line<br>Unstable distribution network | Expected energy not produced<br>Loss of load<br>Faster time to microgrid failure<br>Shorter expected lifetime<br>Degradation of the microgrid performance |
| Microgrid Component [7)14)] | Suboptimal quality component<br>Poor quality design<br>Shallow technical understanding<br>Component aging<br>Wear out component | |

information in an easily digestible format, thereby allowing stakeholders to quickly grasp the scope and scale of the problems at hand. The chart serves as a comprehensive visual catalog that details the distribution of challenges across the key domains integral to rural electrification; technical, financial, and community. Each segment of the doughnut represents a specific domain or subdomain, and the size of each segment is proportional to the number or severity of issues it encompasses. Moreover, by visually mapping these challenges, Figure 3 acts as an invaluable resource for targeted interventions. It aids in the prioritization of issues based on their distribution and impact, helping stakeholders to allocate resources more effectively for problem-solving.

Complementing the doughnut chart in Figure 3, Table 3 breaks down the emerging issues in each each domain and subdomain within rural off-grid microgrids, highlighting their potential to trigger various forms of deterioration in the microgrid system, such as reduced efficiency, increased operating costs, or even early failure. Additionally, Table 3 also summarizes the potential impact associated with each issue, providing a complete picture of the problem at hand. The first section focuses on financial aspects, examining issues like funding continuity, limited initial budgets, and long processing times for research funding. Importantly, it highlights the resultant impacts, such as a preference for the cheapest price selections, limited budgets for operations and maintenance, and a skewed focus on quantity over quality. Community factors comes in the second section. Here, it highlights the parties involved, like governments, donors, contractors, and local residents, and underscores challenges like limited communication due to inequality and discontinuation of contracts. The term "Drop and Go," which refers to the question of project ownership, further captures the pitfalls related to community engagement.

The third section focused on technical aspects, featuring issues like power system deterioration, degraded energy storage, and component aging. It alerts to the real-world impacts of these technical issues, such as expected energy not produced, faster time to microgrid failure, and overall degradation of microgrid performance.

The combination of Figure 3's doughnut chart and Table 3 offer an approach to understanding the deterioration issues in rural off-grid microgrids. Both act as a two-tiered system: Figure 3 provides an overarching framework, while Table 3 fills in the particulars, from financial constraints to technical pitfalls. This holistic representation aids in understanding the interplay of factors that contribute to the deterioration of microgrids and forms the basis for informed and strategic intervention. When interpreted together, these tools offer an integrated, visual, and descriptive framework for stakeholders. This representation not only highlight the different domains and subdomains but also captures the factors contributing to microgrid deterioration.

## 5. Interconnected Impact: Financial, Community, and Technical

This section offers a comprehensive exploration of the interrelations among the financial, community, and technical domains in the management of microgrid systems. The analysis emphasizes their collective significance in determining the overall operation of microgrid systems. In addition to the crucial impact mitigation strategies outlined in Table 3, Figure 4 introduces a comprehensive management framework designed to underscore how they interact and influence one another, revealing a more dynamic connection landscape. This framework aims to provide an understanding of how issues and their subsequent impacts are interlinked across three critical domains within microgrid management: financial, community, and technical.

### 5.1 Financial framework layer

Emerging financial issues are among the most potent factors that can affect the projects and organizations. One of the example is the tendency to focus on the cheapest price selection when sourcing equipment. While this approach may yield short-term financial benefits, it often can result in compromised quality of deliverables, potentially leading to operational challenges. For example, opting for lower-cost, lower-quality components can lead to frequent breakdowns, escalating maintenance costs,

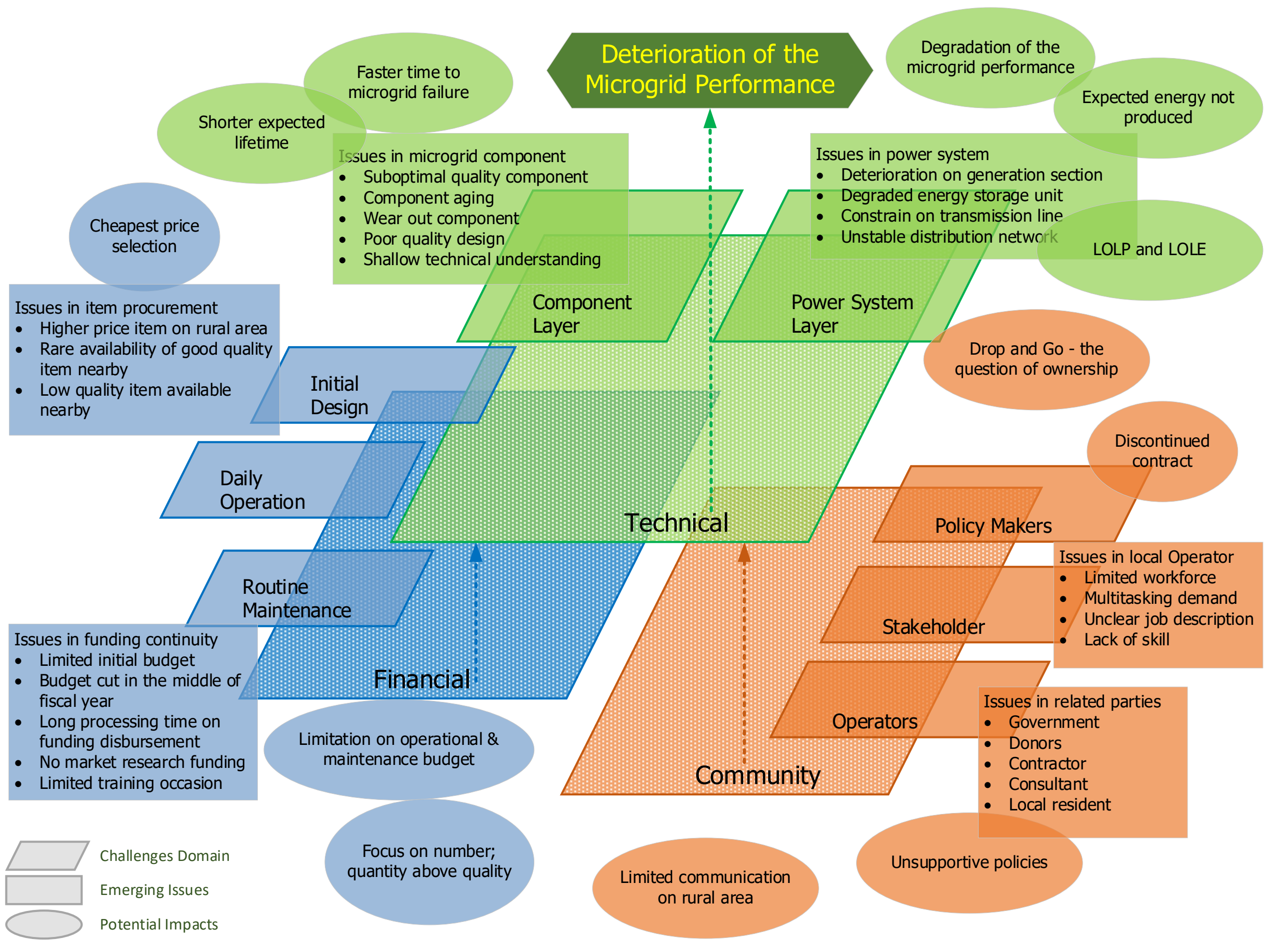


**Fig. 4:** Management framework for rural microgrid on anticipating the deterioration challenges.

and, ultimately, shorter project lifespans. The limited budget for operational and maintenance activities poses challenges in sustaining projects and ensuring their long-term sustainability. Cutting corners in essential operations like routine checks, staff training, or system upgrades can result in a cascade of technical issues that may require costly emergency interventions later on. Additionally, the emphasis on quantity over quality often leads to an unfortunate dilution of project impact. Allocating resources chiefly towards achieving quantitative goals can result in missed opportunities for enhancing the overall impact and effectiveness of projects. In essence, while the financial constraints of a project may necessitate certain limitations, a narrow focus on immediate cost-saving can inadvertently sow the seeds of future challenges.

### 5.2 Community framework layer

Within the scope of microgrid management, the community domain plays an equally pivotal role as the financial domain. The highlighted impacts are as follows: the limitation in communication arising from disparities in social or economic status. Such inequality often stifles constructive dialogue and makes stakeholder engagement a challenging endeavor. When such effective collaboration is hindered, it's challenging to gain collective support for complex projects like microgrids, which demand ongoing, multifaceted community engagement. Another challenge lies in the institutional mechanisms that govern the microgrid project, including policies and support from governments, donors, investors, and contractors. Often, policies may be drafted without adequate consultation with the community they impact, leading to regulations that are unsupportive or even detrimental to the project's sustainability. Moreover, the discontinued contracts disrupt project continuity, creating uncertainty and potential setbacks such as logistical nightmares, loss of community trust, and a cascade of delays. Last but not least is the issue of ownership, commonly known as "Drop and Go," This is where a project is initiated and then effectively abandoned by its originators. It can lead to conflicts and challenges in sustaining community engagement and support, hindering the long-term success of projects.

### 5.3 Technical framework layer

In the microgrid management, the technical domain presents a unique set of challenges that can considerably impact the overall efficacy and reliability of the system. The highlighted impacts in the technical domain are as follows: Expected energy not produced can result in a shortfall in meeting energy demand. Unmet energy needs can lead to broader systemic failures affecting the reliability of power systems. Loss of load is another concern. This occurs when the microgrid fail to provide the amount of power needed to meet current demand, leading to power outages and disruptions. Faster time to microgrid failure indicates a reduced lifespan and increased vulnerability of microgrid systems. This not only jeopardizes the functionality of the microgrid but also necessitates additional financial outlays for repairs or replacements, further straining budgets and resources. This creates a cycle where technical shortcomings contribute to financial and operational instability. Degradation of microgrid performance must not be underestimated. This leads to inefficiencies in energy production and distribution, reduced system reliability, and compromised functionality. Such degradation not only affects the immediate operation of the microgrid but can also disillusion the community it serves. By understanding these technical challenges in greater depth, stakeholders can more effectively strategize to address these issues, ensuring not just the technical soundness of the microgrid, but also its financial viability and community acceptance.

### 5.4 Interconnected challenges between layers

It can be highlighted that the challenges and issues within the financial and the community domain have a direct and significant impact on the technical domain and then resulted in the emergence of deterioration in the power system layer. In the financial domain, an overemphasis on cost-saving measures like selecting the cheapest options can further contribute to the deterioration of technical infrastructure, amplifying the risk of system failures and inefficiencies. Conversely, within the community domain, factors such as limited communication, unsupportive policies, or inadequate local workforce can also contribute to technical deterioration. Furthermore, unsupportive policies from local governments or funding bodies can create bottlenecks in implementing technical solutions, leading to deferred maintenance and rapid system degradation. In summary, by recognizing these challenges connection, stakeholders can prioritize appropriate strategies and interventions to address the root causes of deterioration across all domains. More comprehensive and adaptive strategies can ensure the success and sustainability of microgrid projects across all respective domains.

### 5.5 Open topics for the future direction

This paper focuses specifically on developing a framework to identify and address the deterioration challenge in rural areas. The primary objective is to provide guidance and support in recognizing and mitigating potential emerging issues and deterioration challenges within the microgrid system. While the emphasis is on identification and addressing, the paper also offers some insights into potential future work that can further contribute to the field.

- A detection method should be developed to detect the actual degradation and deterioration in the microgrid component. PV monitoring techniques have been developed and can be further modified for the use of rural microgrids.

- Predicted interference could be anticipated; however, unpredicted interference needs a real-time monitoring system. Therefore, a real-time management strategy is highly suggested to anticipate unpredicted interference, especially from the rural environment.
- Proper maintenance and the availability of well-trained human resources are among the essential factors that can trigger a virtuous cycle of growth of the microgrid. This plan should be developed to adapt to the unexpected disturbance in the rural area.
- The aforementioned microgrid operation plans should only work with boundless continuous funding. A long-term financial scheme should be adopted to facilitate the collaboration between unique parties in a rural energy project.

## 6. Conclusion

The inherent complexities of off-grid microgrid systems, combined with unique challenges posed by rural interferences, can result in significant deterioration of components and overall system functionality. This study developed a comprehensive management framework aimed at analyzing and mitigating the potential deterioration within rural off-grid microgrids. This paper highlighted three critical domains of the rural microgrid challenges, which simultaneously correlated with each other and invoked a potential deterioration, i.e., financial, community, and technical. In the financial domains, funding constraints and procurement limitations were found to hinder the operation of microgrids. Within the community domains, the study conveyed the unique challenges arising between distinctive local operators, stakeholders, and policymakers, which could impact the operation of the microgrid, such as delays in maintenance schedules or inadequate coordination. Unattended financial issues and community issues can eventually affect the technical domain of the microgrid, leading to performance parameters deterioration from the generation section to the distribution network. The findings of this study emphasize the interdependence of these domains and their collective impact on the operation of rural off-grid electrification systems. It is intended that the knowledge in this management framework will be a piece of viable information for the operators and other management entities to identify and mitigate any rural challenges which lead to the deterioration in the operation of rural off-grid electrification systems. The significance of this research lies in its comprehensive analysis of the unique deterioration challenges faced by rural microgrids. This knowledge can inform decision-making and policy development to ensure sustainable and reliable electrification in rural areas. Future works should explore the adoption of non-rural critical development and approaches to be implemented in rural areas.

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### Author Contribution Statement

All authors contributed equally as the main contributors to this paper. All authors read and approved the final paper.

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