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Article

Unveiling the Decision-Making Dilemmas in Mini-Grids: The Intricate Case of Smart Meters

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Abstract: Mini-grids need to imitate the transition path of a traditional grid to maintain their position as a sustainable energy access alternative, while aligning with the objectives of the seventh Sustainable Development Goal. One such strategy is implementing smart-metering solutions to improve business viability and remote monitoring of distributed mini-grid assets. However, selecting smart meters presents a significant challenge for mini-grid operators, primarily due to the installation costs involved and the complexities associated with operating mini-grids in rural areas. Against this backdrop, the current case study' demonstrates the utility of multi-criteria decision aids, such as stochastic multi-criteria acceptability analysis (SMAA), to assist mini-grid operators in making informed decisions concerning smart-meter selection. In addition, practitioners' narratives elucidate how implementing smart metering can function as part of mini-grid operations in rural areas. Furthermore, narratives highlight the importance of considering context-specific conditions to avoid the under-utilisation of smart meters.

Keywords: mini-grids; smart meters; MCDA; pre-feasibility study

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1. Introduction

A recent World Bank report suggests that mini-grids have the potential to provide electricity to 490 million people, as new technologies and falling costs have made them an accessible and viable alternative to a national grid connection [1]. This scenario will require supportive policies, private-sector participation [2,3], a conducive business environment [4,5], and institutional financing [6,7]. In addition, mini-grid operators must adopt smart-grid characteristics to improve financial sustainability and viability [8]. From an energy access perspective, smart-grid characteristics may enable mini-grids to leapfrog the role of traditional power systems in the Global South in the energy access context. Smart grids improve the business viability of mini-grids by facilitating remote monitoring of distributed energy systems [9]. Herein, smart meters play a key role by offering bi-directional communication between the system operator and technical components [10]. Correspondingly, many mini-grid operators have adapted smart meters to control, measure, and manage their assets' technical and economic performance [11]. There is a consensus among energy access practitioners that smart meters could aid in scaling mini-grid business models [12,13]. Despite the importance of smart meters, far too little attention has been paid to their implementation in the existing literature. This article intends to fill this research gap by focusing on smart meter selection and implementation with the help of a case study. The case study setting is a mini-grid company operating in Jharkhand, India.

Selecting the appropriate smart metering setup is crucial for the long-term viability of a mini-grid business, as meters can account for as much as 40% of the total installation costs.

The selection problem resembles a multi-criteria decision problem, as smart meters differ significantly in terms of their characteristics, costs, specifications, and technologies [12]. In such decision-making scenarios, multi-criteria decision aid (MCDA) methods are helpful for decision-makers (DMs) to electrify rural areas through off-grid electrification [13,14]. In practice, MCDA methods support mini-grid operators in choosing from alternatives by considering multiple criteria with conflicting objectives. MCDA tools provide an analytical framework for informed decision-making considering relevant stakeholders' objectives grounded on imprecise information prevalent in real-world problems [15,16]. MCDA has been applied widely to various mini-grid planning and decision problems. Most studies concern energy system planning (e.g., [17–20]). Such pre-feasibility studies are an important tool to evaluate the techno-economic availability of energy resources in the context of community needs, end-user preferences, and the assessment of the social and environmental impacts. However, these pre-feasibility studies seldom account for the practical challenges mini-grid operators encounter in rural areas [21]. These practical challenges include demand uncertainty, limited technical expertise, and techno-economic choices. Moreover, these pre-feasibility studies have not incorporated the selection of smart meters as part of the mini-grid planning. This research gap necessitates a systematic and theoretical analysis of smart meter selection, considering their capital-intensive nature.

Considering the above background, the current article demonstrates the utility of stochastic multi-criteria acceptability analysis (SMAA), an MCDA method [22], to support mini-grid operators for selecting smart meters. The methodological approach involving a single case study aligns with the traditions of MCDA problems in engineering [23]. In addition to presenting the utility of the SMAA approach for smart meter selection, we apply organizational narrative analysis, as proposed by Boje [24], to analyze the interview material. Narrative analysis as a methodological framework facilitates the amalgamation of specific events and processes in a given context [25]. The narratives contextualize practitioners' experiences concerning smart meter use within mini-grid operations in rural areas. Through narrative analysis, interviewees reveal the practical limitations of smart meter installation and maintenance, and the inherent challenges associated with the utility of smart meters in rural settings. Adopting the narrative as a unit of analysis allows us to uncover the nuances and complexities often overlooked in energy research, additionally providing nuances to the available quantitative data [26].

This study offers new insights for mini-grid operators and practitioners. First, the case study catalogues the operational challenges associated with context-specific conditions that may limit the smart-metering approach's utility in rural settings. The reported operational challenges are not adequately addressed in the existing mini-grid literature. Secondly, the study demonstrates the efficacy of MCDA tools in providing valuable insights for the smart meter selection problem, augmenting existing planning studies in the literature. Finally, the hierarchical criteria presented in this study provide a reliable snapshot of the functional aspects of smart metering implementation in rural areas. The proposed hierarchical criteria may be helpful for mini-grid operators as it helps to break down the functional and operational complexities of smart meter implementation into smaller and more understandable characteristics. Overall, this study bridges the existing research gap in the current literature regarding the selection and implementation of smart meters in rural mini-grids.

This article is structured as follows. In Section 2, we provide background on mini-grids and smart meters. Section 3 introduces the case study and data collection, while Section 4 presents the methodology. Section 5 presents the analysis of the qualitative interview material on smart metering implementation. Section 6 presents smart meter selection as an MCDA problem. Before the discussion and conclusion, we illustrate how SMAA is useful for decision making concerning smart meter selection.

2. Smart Meters and Mini-Grid Operations

Mini-grid design and deployment ought to holistically consider economic, technical, and social factors to identify locally appropriate technologies that serve the energy needs of end users in rural settings [27]. From an energy access context, the adopted strategy must align with the local context to navigate the inherent resource constraints associated with designing and implementing mini-grids in rural areas. From a design and implementation standpoint, mini-grids have the following core objectives: electricity generation; energy storage and conversion; end-user consumption; and control, management, and measurement (CMM) [28]. The generation and storage aspects relate to supply reliability. The predominant approach to reliability is identifying viable cost alternatives depending on the local characteristics [13,29]. This approach aims to ensure business viability by balancing the electricity supply and demand. The consumption aspect of the design and implementation strategy focuses on load profile estimation [30] and willingness to pay [31]. The consumption lens pay focuses on ensuring the financial viability of mini-grids. On the other hand, CMM functionality is an essential element of mini-grid planning that addresses numerous challenges, including technological reliability, optimal deployment of constrained resources, demand management, and reduction in supply outages. CMM functionality also addresses other challenges, such as system maintenance, system reliability, business scalability and viability, tariff implementation, and cash flow management. To overcome these challenges, utilities have adopted smart-grid strategies by taking advantage of digital technologies, including smart meters [32,33]. Similarly, Welch et al. supported the smart grid strategy for mini-grids and emphasized the importance of smart meters for addressing operational challenges [34].

Smart meters can provide significant benefits for mini-grid projects in rural areas. They can help address problems with timely rental collection and payment defaults and facilitate the scaling of business operations by offering practical insights into energy use and system reliability [35]. These practical insights encourage DMs to use constrained resources prudently [36]. Smart metering systems also provide tamper protection and risk management [37,38]. Another study argues that implementing smart-metering technologies can mitigate energy theft, reduce social tensions, and improve the viability of off-grid electrification efforts [39]. In addition, smart meters allow different tariff settings for different user groups. These functional characteristics permit shelving unintended new peaks by balancing demand and supply [40]. Taken together, smart meters allow mini-grid operators to address diverse challenges while enabling remote monitoring of day-to-day operations.

The above-mentioned studies present positive aspects of smart metering implementation for mini-grids while considering smart meters as a single technological artefact. This consideration presents an oversimplified view of smart meters as part of mini-grid operations. As a technological artefact, the smart meter is not a single unit; instead, it is part of a configured infrastructure that integrates several technologies, including data communication systems, data management systems, and a web interface to assist with data analytics [41]. Moreover, commercially available smart meters differ significantly in terms of technological configuration. On the other hand, deploying smart meters in rural areas can present additional challenges, such as the lack of reliable network infrastructure for data communication and the limited technical expertise of mini-grid operators. These challenges can be addressed by considering smart meter features and functionalities. The rest of the section briefly overviews smart meter features and functionalities affecting mini-grid operations.

Data communication is the most complex element of a smart-metering setup [42]. Mini-grid operators need to test the technological limitations of data communication in a rural setting to reap the maximum utility of smart meters. It is not easy for mini-grid operators to choose the most appropriate technology for reliable data communication, considering the geographical nature of a typical mini-grid. Popular communication technologies include radio-frequency mesh, low data-rate power line communication, and cellular networks. To evaluate these communication technologies, mini-grid planners must consider data latency and outdoor sensitivity when assessing smart meters. Most smart-metering deployments use two layers of data communication. Generally, the higher communication layer facilitates the backhaul of extensive data from the intermediate server to a database. The second layer of the network, commonly known as the data concentrator unit, typically connects the smart meter and the intermediate server. Few deployments use single-layer communication networks to enable communication. Thus, various criteria must be considered while opting for a smart-metering setup to ensure reliable data communication.

Smart meters enable mini-grid operators to account for cash management from electricity distribution. Herein, given the advantages of pay-as-you-go systems, mini-grid operators often prefer to use smart meters in pre-paid mode compared with post-paid operations. In the prepaid mode, a smart-metering setup uses different data communication technologies to transfer credit to the customer's account. In practice, mini-grid operators often rely on local agents to facilitate cash collection owing to poor network reliability concerning data communication in rural areas. In addition, smart meters can help detect and report electricity theft attempts. Electricity theft is a pervasive problem for off-grid system operators (see [43]) and negatively impacts mini-grid business models' sustainability. One study recommends that mini-grid companies safeguard revenues against electricity theft [44]. To this end, mini-grid operators often install smart meters either on distribution poles or outside walls.

Smart meters allow data collection and permit data analytics to gain insights into electricity generation, electricity consumption, customer payments, customer information systems, and overall system performance. Data analytics enable a multi-dimensional analysis of smart-meter data and may provide useful information reflecting the onsite performance of mini-grids and the evaluation of the business model. A recent world bank report suggests that data analytics from smart meters mainly offer two advantages: reduced operational expenditure of mini-grids and improved customer service quality [45]. These two advantages of smart meters could aid mini-grid development prospects concerning universal electrification efforts by 2030.

Smart meters help mini-grid operators improve and monitor their distributed energy assets and business and revenue models, especially remote monitoring functionalities aid in overseeing the operations of dispersed mini-grids suited for rural areas. Herein, the inherent technological sophistication further increases the complexity of decision problems placed on mini-grid operators considering the energy access context owing to resource constraints, as reported in a case study from India [4].

Overall, smart meter selection as a decision problem significantly affects mini-grid operations. In resource-constrained settings such as rural areas, technological choices with high capital costs, such as smart meters, demand an informed decision-making process. In other words, the decision problem—identifying appropriate smart metering setup—concerns multiple criteria, including technological characteristics, remote monitoring capabilities, and operational capabilities of the mini-grid operator. A review of the mini-grid literature elaborates on similar decision problems and multiple criteria for mini-grid operators [46]. For mini-grids, these multi-criteria are characterized by uncertain and imprecise information [18,20]. As a result, DMs can rely on MCDA methods to identify an acceptable solution among different alternatives by considering the relevant criteria [15,47]. In the case of smart meters, different alternatives can be assessed through MCDA methods by evaluating functionalities, characteristics, costs, operational requirements, and specifications in a given setting. An earlier study demonstrates the usefulness of MCDA tools for selecting smart meters in municipal buildings [48].

To summarize, first, smart metering implementation as part of mini-grid operations positively affects universal electrification efforts in rural areas. Second, smart meter implementation requires informed decision making due to high capital costs, technological complexity, and operational advantages. Herein, MCDA tools could aid informed decision making while safeguarding the interests of mini-grid operators in resource-constrained rural settings.

3. Case Study and Data Collection

The case study integrates onsite experiences relating to smart-metering implementation into academic discourse through narrative analysis. It showcases the application of SMAA to assist operators in making informed decisions when selecting a smart-meter setup for mini-grid operations in rural areas. The study setting is a social enterprise operating in Jharkhand, India, whose name has been anonymized by the request of management. The methodology explains the intertwined complexities associated with smart-meter implementation as part of mini-grid operations. Similar case studies are widely used in MCDA studies in engineering and environmental research [23,49]. The rest of the section contextualizes the case study and provides information concerning data collection.

3.1. Case Study Background

Over the last decade, the Indian government has adopted a two-pronged approach to improving electricity access in rural areas. The first approach involves rapidly expanding the national grid to unelectrified villages. The second is the electrification of poor households through the Pradhan Mantri Sahaj Bijli Har Ghar Yojana (Saubhagya) scheme. With this two-pronged approach, the government intended to achieve universal electrification by 31 March 2019. Subsequently, the Indian government declared near-universal household electrification on 31 December 2018 [50]. The International Energy Agency acknowledges rapid electrification while highlighting the poor reliability of electricity in rural areas [51]. In other words, reliability issues persist in rural communities, as end-users experience frequent blackouts. A survey of rural households in 2020 confirmed these reliability issues [52]. Reliability remains a contradiction in the success story of near-universal electrification. The contradiction also prevails in Jharkhand. A survey from 2021 found that rural households in Jharkhand face similar reliability issues with the national grid [53]. Given this scenario, mini-grids may reduce the frequency and duration of power outages, making them more reliable by serving the energy needs of rural communities in the state.

Against the above backdrop, a mini-grid social enterprise began operations in rural Jharkhand in 2017, and it continues to install solar mini-grids to serve underserved communities. Social enterprises—organizations working on unmet needs by balancing profitability and social impact—are suitable for delivering energy services in rural areas considering market imperfections and resource constraints in low-income settings [54]. To assess viability, the enterprise mainly evaluates population size, household energy requirements, consumer willingness to pay, and commercial energy demand, and follows the build, own, operate, and maintain (BOOM) business model. Due to market imperfections, mini-grid operators tend to exhibit a pronounced inclination towards the BOOM business model, making it a natural choice [55]. Unlike the national grid, where multiple organizations are responsible for decision-making, the BOOM business model requires mini-grid operators to oversee a myriad of decisions concerning technological choices, operations management, resource allocation, revenue collection, and customer management. The complexity concerning the decision-making process presents paradoxical challenges surrounding how different sociotechnical aspects of the mini-grid are designed, managed, and operated [4].

By the end of 2018, the company had installed 40 mini-grids and was planning to install 100 additional mini-grids by 2023. Statistically, the company intended to install four mini-grids every quarter. As with many social enterprises, the company inherently faced resource constraints. These constraints often arise due to various factors, including a necessity to focus on social impact, limited access to financing, and in-house technical expertise. To support the company personnel, a team of experts, which included the first author, provided technical assistance to the enterprise in various areas, such as smart meters, energy-efficient devices, storage options, and process improvements from 2018 to

2019. The technical assistance was financed by the Good Energies Foundation as part of a capacity-building project. The focus of the current article is limited to smart meters.

Since the beginning of solar mini-grid installations in Jharkhand, the enterprise has incorporated smart meters into its technical setup. However, the initial choice of smart meter technology imported from Spain created challenges during onsite deployment, prompting the company to switch to an alternative smart-metering setup. At the time of the capacity building project, the company was facing operational challenges, which were preventing them from realizing the full potential of its smart metering setup. To this end, the management team sought assistance from an expert team to determine the most suitable smart-metering system for their future mini-grids. Such collaborative partnerships are essential in resource-constrained entrepreneurial settings [56,57].

3.2. Data Collection

From the capacity-building project standpoint, the main objective of decision problems was to identify the most suitable smart meter(s) based on the preferences of the mini-grid operator. The expert team assisted the management team in evaluating appropriate smart-metering options for solar mini-grids. The assistance involved proving technical expertise for comparing various alternatives, with the current metering setup as a reference.

To unpack the complexity of decision problem, the expert team gathered qualitative and quantitative information on the company's use of smart meters using a semi-structured questionnaire. The questionnaire was tailored to the respondents' experiences with smart meter implementation, allowing for open-ended responses. In practice, during the semi-structured interviews, all participants were asked the same set of questions, and specific additional questions were included based on the interviewee's occupation. The standard questions were as follows:

- What installation and operational challenges are typically associated with smart meter implementation?
- What are the main technical challenges of smart meter implementation, and how are these challenges affecting mini-grid operations?
- Are you satisfied with the existing process concerning prepaid transactions?
- What smart meter functionalities are essential for mini-grid operations?
- Taking into consideration the overall costs involved, how would you evaluate the performance of the current implementation of smart meters?
- In your opinion, what specific modifications or changes are needed in the current smart meter implementation to address the existing operational challenges effectively?
- What are the main concerns reported by ground-level technicians concerning smart meters?

The data-gathering process lasted four months (December 2018 to March 2019) and included stakeholder interviews, data collection from site visits, identification of alternatives, and the presentation of results to DMs. Stakeholders involved in the data collection process included plant engineers, field technicians, the technical team overseeing metering implementation, the management team (as DMs), and other experts. Upon completing the data collection process, the technical and management teams identified multiple criteria in collaboration with the expert team at the company headquarters in Kolkata. In April 2019, the expert team suggested nine alternatives to the existing metering setup, and the management team selected four alternatives for further evaluation. The management team discarded two alternatives due to their prior experience with imported smart meters. Additionally, other alternatives were rejected mainly due to capital cost. The expert team then presented a comparative analysis of the remaining alternatives, including the existing setup, in June 2019. The comparative analysis provided an overview of each alternative without MCDA support.

In this article, the authors expand on the original decision problem by utilizing the data collected during the project period to showcase the application of SMAA to ranking alternatives based on multiple criteria analysis to aid DMs. In addition, the current article presents an analysis of the qualitative data using narrative analysis. The narrative analysis highlights invisible nuances by elucidating the overarching themes [58]. The interviews at company headquarters, specifically with DMs, focused on organizational capabilities and overall utility in the purview of smart metering implementation. All interviews were recorded, transcribed, and analyzed. Table 1 presents information related to the respondents.

Table 1. Qualitative interviews.

Title	Identifier	Language(s) of Narrative
Regional manager	A	English and Hindi
Assistant manager	B	English and Hindi
Technical manager	C	English and Hindi
Assistant technical manager	D	English and Hindi
Deputy country director	E	English

4. Methods and Methodology

This case study used a multi-disciplinary approach, a combination of SMAA and narrative analysis, to achieve its research objectives. The current section explains these two methods.

4.1. Stochastic Multi-Criteria Acceptability Analysis (SMAA)

Concerning the social enterprise's decision problem, piloting is one way to compare different smart meters. The piloting process involves the implementation of new technology for testing and evaluation purposes. However, piloting is expensive for mini-grid companies in rural, resource-constrained settings. Another approach is to rely upon descriptive methods without any methodology. This approach is inadequate for structuring complex problems involving conflicting objectives. Therefore, a more suitable option is to compare different meters using MCDA methods.

MCDA methods are useful in decision-making processes to manage imprecise information, criteria, uncertainties, and DM preferences, thereby replacing the intuitive selection of alternatives with justified decision models. To analyse the decision problem in this instance, we opted for SMAA [22]. SMAA is an MCDA tool for evaluating alternatives regarding multiple non-commensurate criteria [59]. SMAA was selected as it can be applied to decision problems with ordinal and cardinal criteria, where information is imprecise or uncertain. This section briefly describes the SMAA method. For a detailed overview and application of SMAA, see [60].

SMAA relies on Monte Carlo simulations to produce MCDA parameters. The simulation model randomly generates criteria measurements and weights from their corresponding distributions at each simulation round. One study recommends the number of iterations to be between 10,000 and 100,000 [61]. The current study involves 10,000 iterations. The alternatives are ranked based on utility function values, and the corresponding evaluation statistics are collected. Preference information can be considered flexibly in SMAA. Monte Carlo simulation rejects weights that do not satisfy the constraints defined in the MCDA model.

SMAA methodology helps DMs choose their most preferred alternative from a discrete set of r alternatives $\boldsymbol{x} = \{x_1, x_2, \ldots, x_r\}$. These alternatives are evaluated based on multiple criteria, where s is the number of criteria. The decision model combines the criteria measurements with DMs' preferences by calculating a utility function $u(x_r, \boldsymbol{w})$, where $\boldsymbol{w}$ is a set of subjective weights given by DMs concerning different criteria. In simple terms, the utility function expresses different criteria with a numerical value to represent the preference for each combination of criteria. The utility function can have different shapes. Current SMAA implementation uses an additive function with partial utility in this case. For a detailed description of additive partial utility, refer to [62]. The additive utility function computes the overall utility as a weighted average of the partial utilities of alternatives:

$$u_r = \boldsymbol{u}(\boldsymbol{x_r}, \boldsymbol{w}) = \sum_s w_s u_s(x_{rs})$$

The partial utility function $u_r(x_{rs})$ maps the criteria measurements to the interval $[0, 1]$, where 0 is the worst value and 1 is the best value. The weights are normalised in SMAA to be non-negative, and their sum is 1. The set of feasible weights is defined below:

$$W = \{\boldsymbol{w} | w_s \geq 0 \; and \; \sum_s w_s = 1\}$$

As mentioned in the introduction, SMAA is a useful MCDA tool for aiding DMs in dealing with uncertain criteria measurements and approximate weights. Stochastic variables represent uncertain criteria measurements $[x_{rs}]$ using the joint density function $f_x(\boldsymbol{x})$. Similarly, the joint density function $f_w(\boldsymbol{w})$ represents imprecisely known weights. If weight information is missing, then SMAA uses uniform distribution.

SMAA, as a method, accommodates ordinal and cardinal criteria measurements [63]. This versatility offers strategic flexibility in the decision-making process. However, measuring cardinal values for each criterion is often expensive and time consuming. Despite ambitious efforts, the measurements remain uncertain or inaccurate for many real-life decision problems. Ordinal criteria measurements are helpful in this respect, as they allow a combination of qualitative and quantitative information to be represented by ranking the alternatives. SMAA treats ordinal criteria in the following manner. For example, suppose alternative A is better than C, which is better than B concerning some criterion. In that case, SMAA assigns a partial utility of 1 for alternative A and 0 for alternative B, and randomly generates a utility value in the interval $[0, 1]$ for alternative C following a uniform distribution. See [61] for more details.

MCDA methods often use a criteria hierarchy to deal with the superordinate and subordinate relations between different criteria. Similar criteria often lead to sub-criteria at successively lower levels, forming a hierarchical tree structure. In this application, we extended the SMAA method to treat hierarchical criteria. The root node of the criteria hierarchy was $j = 0$. The main-level criteria were $J(0)$. Leaf nodes in the hierarchy represented the lowest-level criteria without sub-criteria. The partial utility of the lowest-level criterion j was $u_j(x_{r,j})$ and $u_j(.)$ was the partial utility function for criterion j, converting the measurement to the range [0, 1], where 0 was the worst and 1 was the best value:

$$u_r^j = \begin{cases} \sum_{k \in J(j)} w_k u_r^k & \text{When node } j \text{ had sub} - \text{criteria } J(j) \\ u_j(x_{r,j}) & \text{and node } j \text{ was a leaf node} \end{cases}$$

In the case of a criteria hierarchy, the weights (w_j) were normalised separately at each non-leaf node:

$$W^j = \{\boldsymbol{w} | w_k \geq 0 \; and \sum_{k \in J(j)} w_k = 1\}$$

SMAA calculates various descriptive measures for assessing the alternatives. The main measures are explained below:

- The acceptability index (a_r) measures the share of different valuations making the alternative x_r a preferred alternative. Acceptability indices categorise alternatives stochastically within the range $[0, 1]$. A near-zero acceptability index (e.g., $a_r < 0.05$) is never considered as best with the assumed MCDA model.
- The rank acceptability index (b_r^i) generalises the acceptability index by measuring various weights that grant alternative x_r rank i. A near-zero rank acceptability index indicates that the alternative will never obtain rank i. An alternative with high acceptability for the worst ranks should be avoided.

- The central weight vector (w_r^c) characterises the expected centre of gravity of an alternative x_r when it is most preferred. The central weights without preferential criteria allow for an inverse approach to MCDA. In this case, the central weights allowed DMs to understand how different weights corresponded to different choices and made them preferred alternatives [64]. In general, the central weights are undefined for incompetent alternatives.
- The pair-wise winning index (c_{ij}) is the probability for alternative i to be more preferred than alternative j. The pair-wise winning index helps exclude alternatives that are dominated by others.

4.2. Validity of SMAA Results

To ensure the validity of MCDA results, the chosen method ought to align appropriately with the decision problem. Moreover, the problem must be well-defined in terms of both criteria and alternatives. Lastly, accurate measurements of criteria and preferences are crucial factors for maintaining the validity of the analysis. However, MCDA models often need to deal with incomplete, imprecise, and uncertain information on the evaluations and preference model parameters.

SMAA was selected for the smart meter selection problem, because of its flexibility in handling mixed ordinal and imprecise cardinal criteria, and uncertain or absent preference information. Moreover, the validity of SMAA, as a MCDA method, is supported by existing real-life applications in academic literature (see examples: choice of district heating [65], renewable power production at Moroccan airports [66]). A recent acdemic work reviewing SMAA methods of applications presents the theoretical development of SMAA and its robustness by evaluating 118 published articles in scientific lierature [60].

In addition, a team of experts collaborated with DMs to establish the alternatives and criteria. Likewise, the set of criteria used in the SMAA model comprehensively captured all the features relevant for mini-grid operations. In addition, the criteria met the general requirements for model validity specified by Keeney and Raiffa [67] for decision problems with multiple objectives and different trade-offs: completeness, operationality, non-redundancy, and minimality.

4.3. Narrative Analysis

Numerous qualitative data analysis methods, such as grounded theory, thematic analysis, and discourse analysis, are available to analyse semi-structured interviews. In this instance, we opted for narrative analysis owing to its ability to capture otherwise invisible nuances within organisational settings [68]. Moreover, semi-structured interview responses usually take a narrative format, where respondents recollect events in sequence and with consequences. In narrative analysis, the recollected events were 'selected, organised, connected and evaluated' [69]. The narratives illuminate how different DMs in the rural social enterprise reflect on the smart-metering setup. The main limitation of narrative analysis is that the interview setting influences narratives and to whom the narrator is talking [70] (p. 180).

As a research method, narrative analysis provides critical insights for energy research [26,71] and has become increasingly popular among social science researchers. As mentioned in the introduction, for this study, we relied on Boje's approach to narrative analysis, which considers organisations as storytelling systems [24]. Practically, people within an organisation recollect organisational endeavours and recount stories of success and failure concerning different events and processes. Collected data was organised to identify meaningful patterns for elucidating how the smart-metering setup adopted functions as part of mini-grid operations at a grass-roots level.

Essentially, the narrative analysis employed in this article considers the operational experiences of the mini-grid enterprise as events with inherent sequences and consequences. The experiences on the field level, where unexpected and unwarranted operational complexities unfold, accentuate invisible tension points in mini-grid operations. Often, mini-grid literature seldom features these rural onsite experiences, as grander narratives predominantly focus on positive narratives of smart meter diffusion in rural settings on a macro level. Against this background, the narratives presented in this article may help mini-grid practitioners adopt strategies for achieving smart-meter implementation objectives in rural settings.

To summarize, the current study relies on SMAA to evaluate smart metering alternatives and employs narrative analysis as the qualitative data analysis method to contextualize the onsite experiences of the mini-grid operator. SMAA was selected for MCDA analysis because it can handle imprecise information concerning multi-variate decision problems, whereas narrative analysis was chosen because it offers greater depth, explanation and meaning for analysing qualitative material.

5. Smart Meters: A Decision-Making Dilemma

Mini-grid operators have benefited from significant improvements in the quality of system components, such as photovoltaic panels, batteries, and inverters, over the last decade [45]. Although smart meters have become more widespread in recent years, their effectiveness varies depending on their overall utility in rural settings, as indicated in the narrative analysis presented below. As the following accounts suggest, the company faces various operational challenges despite substantial investments in its smart-metering setup. The implementation of smart-metering architecture has failed to deliver the promised advantages for the company's mini-grid operations. Our narrative analysis reveals that the metering architecture was misaligned with the heterogeneity of mini-grid operations in rural areas at the time of the study.

For two reasons, pre-paid energy meters are essential for the company's mini-grid operations. First, the pre-paid business model avoids social tension in rural settings. Second, this is the easiest payment model option for low-income rural consumers. When asked about the objective of smart meters, Respondent A stated, "Smart metres with pre-paid system reduces conflicts with customers on bill payments, especially here [referring to rural areas]", and continued, "With smart metres, we can compare cash coming from different sites with the [smart meter web portal]". By framing their response in this manner, Respondent A stressed the importance of prepaid smart meters as the most efficient way to monitor revenues from cash transactions. Respondent B expressed a similar view on prepaid meters, "Our business model works only with prepaid mode; otherwise, bill collection will be difficult in rural areas". In other words, the company opted for smart meters to obtain the benefits of prepaid functionality. In addition, the regional manager stressed the importance of revenue monitoring features within a smart metering setup. These narratives aligned with conventional prepaid mini-grid business models within a rural setting.

The company has employed a smart-metering system that utilizes a 20-digit vend code and a mobile application based on Bluetooth technology to enable prepaid transactions. The company must register plant engineers' mobile numbers with the smart metering web portal to implement automatic prepaid energy credits transfer to end users. The registered mobile numbers will receive a 20-digit vend code via the mobile application, which can be prepaid credits to a specific smart meter corresponding to unique customers. The smart metering setup uses a customer information system for identifying energy meters corresponding to unique end users. The mobile application ensures secure digital transactions and minimizes fraudulent activities. However, the digital transaction will only be completed when the registered mobile phone is near the smart meter, within a range of 10 m. Then, the mobile application uses Bluetooth technology to establish a secure connection with the smart meter and enables the transfer of prepaid energy credits to end users.

The following narratives suggest that the company has not effectively utilised the full potential of the smart metering setup described above. Respondent C explained the downside of the existing top-up process for prepaid transactions, "Our plant engineers, with the help of local staff, manually enter the 20-digit vend code to transfer pre-paid-energy credits. They carry a ladder to input the code as meters are mounted on the pole" (Figure 1). The respondent added that, in addition, "the mobile application does not work as we imagined". This narrative illustrates the drudgery involved in recharging, which seems to have surprised the company personnel in contrast with the pre-paid process described above. Respondent D, who works with plant engineers, explained the rationale behind the drudgery, as follows:

Figure 1. Manual top-up process.

> "The mobile application [refers to Bluetooth application] is registered with a mobile number [of a plant engineer]. We need to contact [the smart meter manufacturer] every time the plant engineer number changes. This is time taking, so we avoid contacting [the manufacturer]. Our plant engineers need to go near the pole for the mobile application to work in any case. So they don't complain about the manual entry [of 20-digit vend code] as local staff helps them".

The above narrative provides a positive interpretation of operational challenges posed by the smart-metering setup, indicating that the perception of these issues varies depending on the role of the employee in question. Moreover, the assistant managers' account indicates the limitations of mobile applications from a practical perspective, as Bluetooth works only within a short range, up to 10 m. This distance limitation creates another operational challenge for the plant engineer, who must know the customer's location in advance. When asked about the significance of the plant engineer's mobile number concerning the ineffectiveness of the Bluetooth mobile application, Respondent D stated:

> "Initially, our company gave mobile phones [with pre-paid connections] to plant engineers with the Bluetooth application installed. This proved problematic when people resigned from the company [which required the mobile phone to be collected and handed over to a new plant engineer]. So, we asked them [referring to new plant engineers] to install the application on their mobile phones. Most of

them do not want to install the application as it affects mobile performance. I have experienced it personally as our [mini-grid] sites have more than 100 customers".

Initially, when the company had few plants, it was not difficult for management to ensure that the mobile phones were handed over to new plant engineers. However, as operations began to expand rapidly, management instead requested the plant engineers install the Bluetooth application on personal mobile devices to avoid the inventory management of mobile phones. Based on the narrative, plant engineers are hesitant to use the mobile application as it can negatively impact their mobile device's performance owing to having many customers. The negative impact, in turn, added an additional layer of complexity concerning smart meter use at the plant level, stemming from unforeseen complexities of technical configuration. Echoing this plant-level operational challenge, Respondent C highlighted an operational challenge with the existing pre-paid process:

"At present, the top-up [or pre-paid] process requires manual intervention despite having smart meters. The plant engineer sends a [WhatsApp] message to the regional office for top-up, and an operator [with login credentials] will top-up using the customer meter number. The generated [vend] code is sent back to the plant engineer [via WhatsApp message] for a top-up".

The above narrative implies that the company relies on a manual top-up procedure, despite investing in smart meters. As a result of the above-mentioned operational challenges, WhatsApp is utilised for communications related to pre-paid requests and vend codes. All interviewees implied that the manual process resulted in mistakes, creating further operational challenges.

Based on the following narratives, weather conditions in Jharkhand pose another challenge to the company. Respondent E commented: "Some of our metres often get damaged due to frequent lightning in this area. We sought help from our supplier too. Their engineers could not offer any solution". This issue was also mentioned by Respondent C, who clarified that it is not only smart meters that are affected by lightning, but a variety of plant components. The supplier of smart meters suggested improving lightning protection for poles with smart meters (See Figure 1). However, this solution is not necessarily feasible due to the cost and dispersion of rural end users.

6. Decoding Smart Meter Characteristics Using Multi-Criteria

The narrative analysis presented above suggests that the existing smart-metering setup created unforeseen operational challenges for mini-grid operators. These challenges could further complicate mini-grid operations, which are inherently complex. As the narratives reveal, the mini-grid company underutilises smart meters as the operators in rural markets have limited knowledge of the diverse characteristics and functionalities of smart-metering solutions. In such situations, a smart-metering setup should preferably be included in the pre-feasibility analysis. Here, mini-grid operators could use MCDA tools as part of pre-feasibility studies to aid in evaluating different smart-metering options.

As mentioned in Section 4, DMs selected these five alternatives including the existing smart metering setup (SM1). Five smart meter alternatives are listed in Table 2 with their abbreviations and descriptions. While SM1 and SM2 are immediately available, other meters require advanced purchase orders to avoid logistic delays.

Table 2. Smart meter alternatives.

Abbreviation	Communication Technology for Top-Up	Location	Availability
SM1	Bluetooth and mobile application	Pole	Mass-produced
SM2	Cellular and mobile application	Pole	Mass-produced
SM3	RF and cellular with mobile application	Pole	Purchase order
SM4	RF and cellular with intermediate server	Pole	Purchase order
SM5	Field-area network-enabled smart meter with intermediate server	Ground mount	Purchase order

During the capacity building project, the expert team evaluated the alternatives without using MCDA tools, as mentioned earlier. When considering the selection of smart meters, it is important to take into account four intuitive criteria for MCDA: economic factors, the top-up process, metering setup, and functionality. However, the narratives surrounding operational challenges underscore the significance of two additional non-intuitive criteria: usability and design. These two criteria encompass the overall effectiveness of smart meters. From a design perspective, smart metering implementation in rural areas often requires customized solutions with greater flexibility due to dispersed households and unreliable communication technologies. Customization and flexibility can ensure that the smart metering system is optimized for the context-specific requirements of rural areas. The usability of a smart metering setup affects its performance and justifies its capital costs. To this end, the usability criteria should also consider the suitability for the local context, service offered by the supplier, overall complexity, technological maturity, and expertise required.

Table 3 lists six main criteria considered for informed decision making. The main criteria are further broken down into 19 sub-criteria within a hierarchical structure to capture the functional, operational, and technical characteristics of smart meters in rural settings. While the economic criterion was measured on a cardinal scale, the other criteria were assessed only on an ordinal scale. The utilization of ordinal scales is widely prevalent in MCDA problems. To rank the alternatives, the project team relied on their expert judgment and made ordinal assessments. The criteria measurements for SMAA models are presented in Table 4, with the sub-criteria being measured ordinally, except for the economic criteria. Ordinal criteria focus on the qualitative or subjective judgment of DMs and experts. In this article, ordinal criteria were evaluated considering the overall variance perceived by the authors. In addition, this study drew upon earlier research conducted on smart meters as a reference for ordinal criteria [47]. For example, the overall complexity of a smart metering setup was measured with a scale ranging between 1 and 4, whereas flexibility from a design perspective was measured with the scale ranging between 1 and 5.

Table 3. Main criteria and sub-criteria for smart meter evaluation.

Main Criteria	Sub-Criteria	Explanation
Economic	E	Annuity on initial investment and total operational costs
Top-up	T1	Human intervention required for top-up
	T2	Ease of accounting top-ups across multiple mini-grids
	T3	Time required for handling top-ups
	T4	Outdoor sensitivity of communication technology
Metering setup	M1	Ease of repair and replacement in the case of meter faults
	M2	Ease of installation
	M3	Modification required for metering enclosures compared to the reference scenario
Functionality	F1	Monthly reports for evaluating individual plant performance
	F2	Customized reports with infographics combining the performance of multiple plants
	F3	The effort required to modify tariff and load limits
	F4	Periodic alerts to aid mini-grid operators
Usability	U1	Suitability for the local landscape and built environment
	U2	Service request handling capacity of the supplier
	U3	Overall system complexity
	U4	Technological maturity of the system
	U5	Operational expertise required for installation and maintenance
Design	D1	Level of customization for mini-grid operations and rural settings
	D2	Flexibility from an organizational perspective

Table 4. Criteria measurements with weights given by operational team and the preference information of the management team.

Main Criteria	Sub-Criteria Weights	SM1	SM2	SM3	SM4	SM5
Economic	1.00 (E)	500 ± 10%	580 ± 10%	430 ± 10%	470 ± 10%	448.5 ± 10%
Top-up	0.40 (T1)	5	3	1	1	2
	0.40 (T2)	5	5	1	3	3
	0.10 (T3)	5	1	1	3	3
	0.10 (T4)	1	3	3	2	5
Metering setup	0.50 (M1)	1	1	4	2	1
	0.25 (M2)	1	1	4	2	3
	0.25 (M3)	1	1	4	2	3
Functionality	0.40 (F1)	3	1	2	1	1
	0.10 (F2)	3	2	2	1	1
	0.40 (F3)	3	2	2	1	1
	0.10 (F4)	3	3	1	2	1
Usability	0.25 (U1)	1	3	2	3	4
	0.20 (U2)	1	1	3	2	4
	0.15 (U3)	1	2	3	2	4
	0.15 (U4)	1	1	4	3	1
	0.25 (U5)	1	2	4	2	3
Design	0.40 (D1)	5	3	2	2	1
	0.60 (D2)	1	1	5	3	2

Preference information for main criteria as per the management team: Economy > Top-up, Metering setup > Functionality, Usability > Design.

Economic criteria are an essential consideration when making decisions in resource-constrained settings. In a hierarchical model, economic criteria encompass capital costs and operational costs. The SMAA model presents the economic criterion using the annuity factor by combining investment costs and total operational costs for five years. The investment cost (I) for each smart-metering setup was estimated based on price information provided by the supplier, which includes the cost of the metering enclosures and protection circuitry. The operational costs (O) were computed considering communication topology and information provided by the supplier. For the total cost (C), if financed by an effective interest rate of r for n years, then the annuity of total economic costs A is calculated as follows:

$$A = \left(\frac{1}{\sum_{i=1}^{n} (1+r)^{i}} \right) C,\ where\ C = I + O$$

The prepaid mechanism offers end-users flexibility and allows customers to purchase electricity in small amounts. As a functionality, this top-up process plays an instrumental role in mini-grid operations. Thus, including the top-up process as part of the MCDA analysis is important. To this end, based on the narrative analysis and the company personnel inputs, we identified four sub-criteria—required human intervention, ease of top-up, time required for a top-up, and outdoor sensitivity of communication technology. Given the diverse nature of the top-up process, these criteria are represented ordinally between 1 to 5.

The metering setup criterion considers installation and maintenance aspects of smart meters as a socio-technical configuration in rural areas. In practical terms, metering setup, as the main criterion, focused on ease of installation, repair, replacement, and modification of existing enclosures (see Figure 1). Alternatives were ordinally measured against the existing metering setup. These criteria were ranked between 1 to 4.

Smart-metering solutions, by design, can perform a range of functional tasks, where tasks are designed to accomplish particular undertakings from a sociotechnical design perspective. Based on the available qualitative material, the mini-grid company identified four essential functions and prepaid functionality. They are monthly reports at the plant level, customized reports that combine the performance of different plants, the ability to modify tariffs and loads to cater to changing business needs, and periodic alerts reflecting the company's overall performance. Unlike the economic criterion, these criteria were measured ordinally.

The usability of smart meters is a crucial factor affecting mini-grid operations in rural areas. In the SMAA model, usability is defined as the functional aspects of a smart meter within a specific setting, considering the limitations faced by mini-grid operators. Usability is often included in MCDA problems, and this case study identifies several sub-criteria that contribute to the usability of smart meters, including system complexity, technological maturity, and operational expertise. Due to usability's subjective and immeasurable nature, sub-criteria are often measured ordinally.

As the narrative analysis revealed, rural mini-grid settings need a distinct technology design perspective to address issues such as inadequate worker skills and resource constraints. Thus, we considered design as an additional criterion to measure the suitability of smart-metering solutions for the rural mini-grid market segment. In practice, this hierarchical criterion assessed the level of customisation offered by each smart-metering alternative and overall flexibility from an organizational perspective. Given the diverse nature of different smart meters, these criteria were ranked between 1 to 5.

7. SMAA Analysis: Evaluating Smart Metering Alternatives

The evaluation of various smart metering alternatives involved the application of the MCDA method in three phases. Each phase of SMAA evaluation involved 10,000 iterations to ensure a robust analysis. This phase-wise approach with 10,000 iterations ensured a more thorough and reliable assessment of the alternatives [62]. The first phase involved performing an SMAA analysis using the analytical hierarchy methodology with uniformly distributed central weights without considering the decision-makers preferences. Here, the uniform distribution represented incomplete preference information concerning real-world problems [68]. In the second phase, the MCDA model considered normalized weights for sub-criteria (see Table 4) based on the inputs provided by the operations team. The main criteria weights were unconstrained in this analysis. The third-phase model used preference information (see Table 4) provided by the DMs as the main criteria. As per management, economic criteria outweighed all of the other criteria, whereas design aspects warranted the least preference.

7.1. MCDA Model without Preference Information

Figure 2 presents the rank acceptability indices (b1, b2, b3, b4, and b5) for the smart-metering alternatives based on the analytical hierarchy methodology without preference information. The figure shows that SM4 received the highest acceptability (37.1%) for the first rank (b1), indicating that it may have been the preferred choice. SM1 received a rank acceptability of 30.8% for the first rank. The proximity between the rank acceptability of SM1 and SM4 indicated the need for subsequent analysis, as the preference information of the DMs had the potential to alter ranks. SM2 received a first-rank acceptability of 15.9%, followed by SM5 (14%) and SM3 (2.2%). Notably, SM2 received similar rank acceptability indices for the second, third, and fourth ranks. The similarity may have been due to SM2 being functionally better than all of the other alternatives. The dominance of functionality is apparent from the central weight in the case of SM2 (see Figure 3). The central weights revealed what kinds of preferences were favorable for each alternative. For example, alternative SM4 was favored by a high weight on top-up procedures (51.6%), while SM5 was favored by an emphasis on the top-up procedure (28.2%) and functionality (23.8%). In addition, the inconclusiveness of the model is apparent from the pair-wise winning indices (see Table 5). For example, SM1 was a better alternative than the other smart meters, with probabilities of 48.22%, 73.95%, 48.36%, and 43.92%. In other words, this MCDA model indicated the need for subsequent analysis, as no alternative predominated each other. The need for subsequent analysis is apparent from the pair-wise winning indices of SM1, SM2, and SM4 in Table 5.

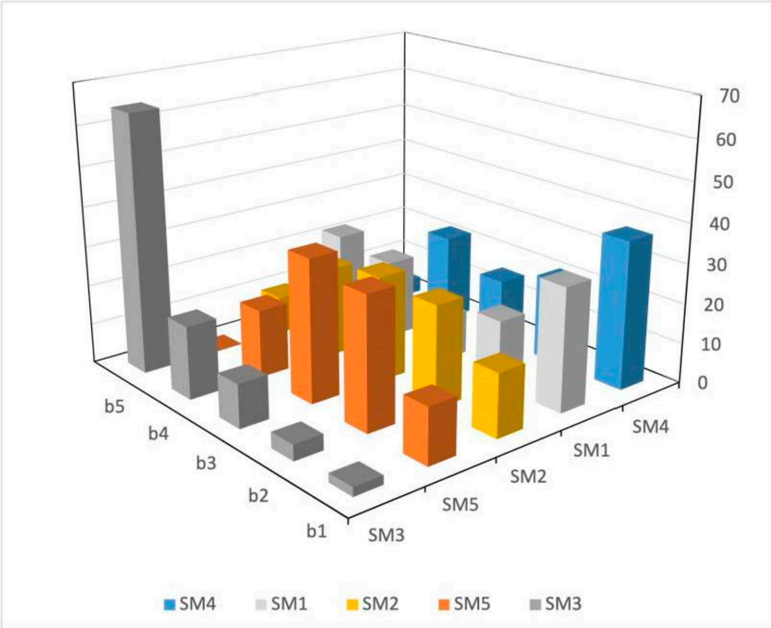

Figure 2. Rank acceptability indices (b1 to b5) of alternatives expressed as percentages without incorporating decision makers' preferences.

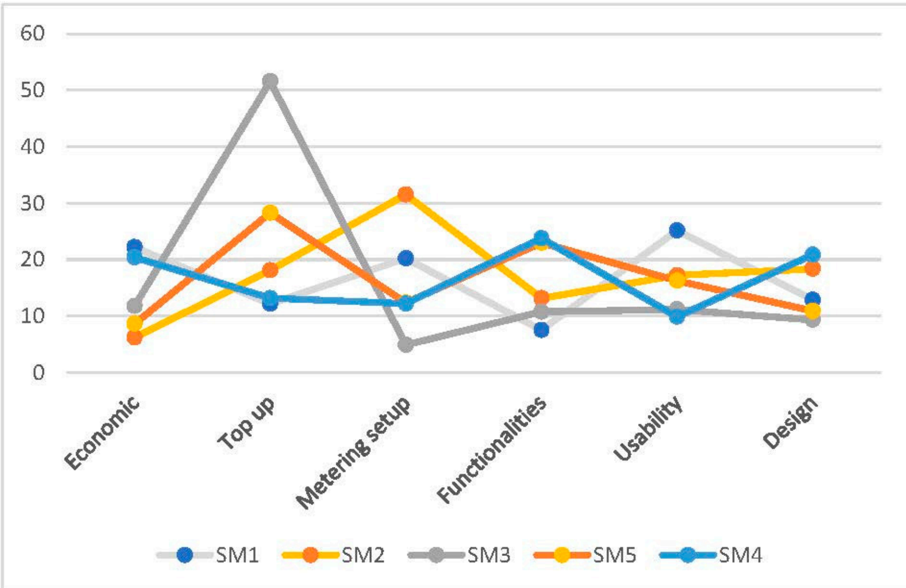

Figure 3. Central weights (expressed as %) for the SMAA model without preference information.

Table 5. Pair-wise winning indices.

Alt	SM1	SM2	SM3	SM4	SM5
SM1	0	97.16 (48.22)	96.14 (73.95)	56.36 (43.92)	83.47 (48.36)
SM2	2.84 (51.78)	0	60.72 (79.06)	4.55 (41.21)	24.1 (43.47)
SM3	3.86 (26.05)	39.28 (20.94)	0	1.69 (8.41)	15.34 (5.59)
SM4	43.64 (56.08)	95.45 (58.79)	98.31 (98.59)	0	83.17 (58.69)
SM5	16.53 (51.64)	75.9 (56.53)	84.66 (94.41)	16.83 (41.31)	0

7.2. MCDA Model with Preference Information of Operations Team for Sub-Criteria

After the first phase of analysis, the main objective was to consider how different sub-criteria affected the decision problem, particularly how the information provided by the operations team affected smart-meter selection. The qualitative information was quantified as preference information in the case of different sub-criteria with the support of an expert team. Figure 4 presents the rank acceptability indices from the operations team perspective. The first-rank acceptability of SM4 improved to some degree (37.4% → 43.1%), while SM1, SM2, and SM5 were still relevant, as their first-rank acceptability remained significant from an MCDA perspective. In other words, these three alternatives were competitive with SM4. With the preferences of the operations team taken into account, the result for SM3 was very similar to that obtained from the first model. Overall, SM4 was the strongest candidate for the first rank in the first two models, followed by SM1. If the mini-grid company continues its existing setup, then SM4 will be eliminated. In addition, the pair-wise winning indices from Model 2 were similar to those from Model 1. As a result, we have not presented the pair-wise indices from Model 2 in this article. Overall, this model also suggests the need for subsequent analysis.

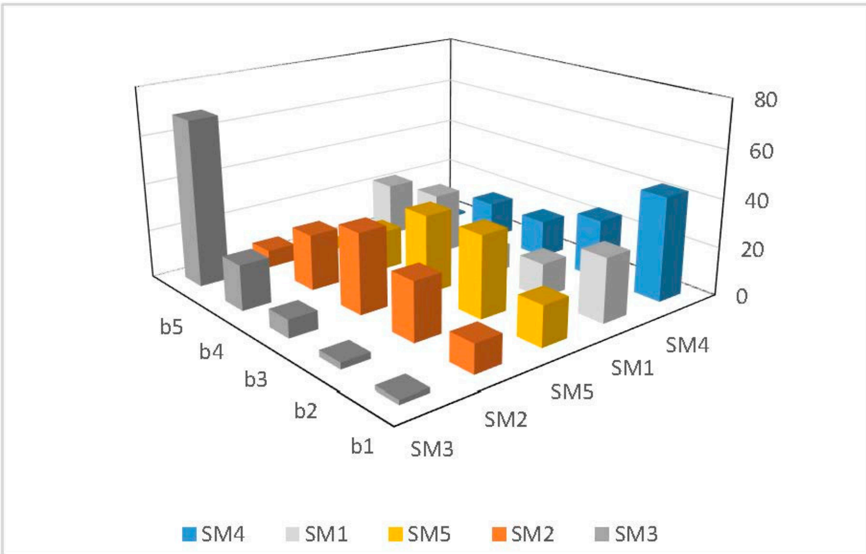

Figure 4. Rank acceptability indices (b1 to b5) of alternatives expressed as percentages with the preference information of operational team for sub-criteria.

7.3. MCDA Model with Preference Information of the Management Team for Main Criteria

The third SMAA model considered the preference information provided by the management team as DMs for the main criteria. The preference information was represented ordinally in the model (see Table 4). The management team gave the highest importance to the economic criterion, followed by the top-up procedure, while the design aspects were given the least importance. The other two criteria received equal importance. Figure 5 presents the rank acceptability indices for each alternative. Compared to the previous models, the rank acceptability indices for this model indicate a clear pattern. For example, SM2 and SM3 received 0% acceptability for the first rank, and both are unfeasible alternatives. The first-rank acceptability of SM4 improved significantly due to the emphasis on the economic criterion. Moreover, SM1 and SM4 clearly dominated over all the other alternatives. The dominance is apparent from the pair-wise winning indices in the case of SM1 and SM4 (Table 5), which show that these metering setups were considered superior to all other alternatives. For example, the probability of SM1 being preferred over SM2 was 97.2%. Similar observations can be observed in the case of SM4.

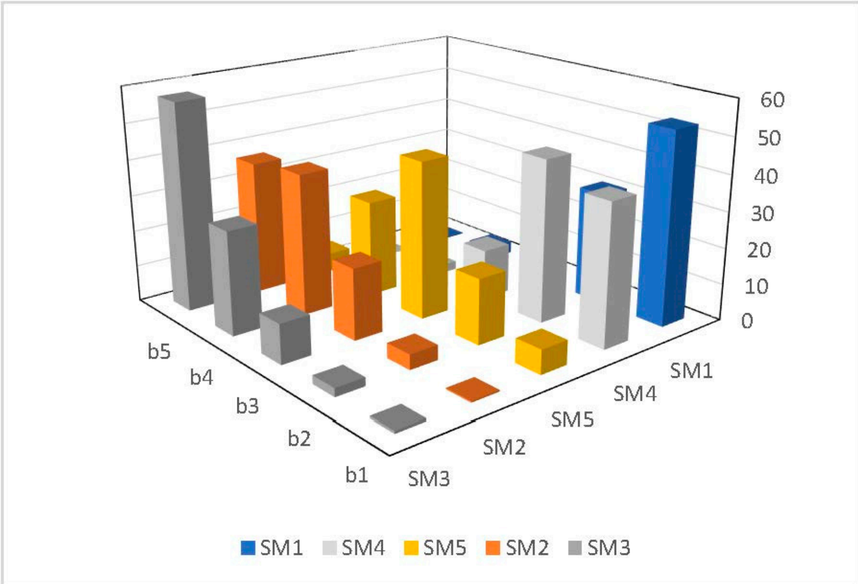

Figure 5. Rank acceptability indices (b1 to b5) of alternatives expressed as percentages with the preference information of the management team for the main criteria.

8. Discussion

Much of the conversation around mini-grids highlights smart meters' importance and advantages in rural settings. There is little discussion in the literature about how the choice of smart meters functions at a plant level in resource-constrained settings. Against this background, this article used a case study to showcase the application of SMAA, an MCDA tool, to aid DMs in evaluating smart-metering solutions. The SMAA method was applied to rank different smart metering alternatives. The MCDA approach involved a set of sub-criteria, including, but not confined to, economic criteria. In addition, we drew on onsite experiences to illuminate the limitations of smart metering in low-income rural settings utilizing narrative analysis. This multi-disciplinary approach—combining qualitative and quantitative research methods—provided the following insights.

In general, widespread optimism and consensus prevail in mini-grid literature concerning the role of smart metering infrastructure as a key component for business viability. Despite this broad agreement, there are still gaps between the potential for smart meters in low-income settings and their implementation in rural areas, as suggested by the narrative analysis, which has revealed the following from a sociotechnical perspective.

First, the narratives illuminate the unforeseen operational challenges the mini-grid social enterprise faces. A myriad of sociotechnical factors have contributed to these operational challenges. For example, plant engineers are reluctant to use the Bluetooth mobile application, citing a negative effect on their mobile phone performance. As a result, the company personnel continue to rely on manual top-up processes. The reliance on manual operations and infrequent mobile application usage limits the remote monitoring capabilities and necessitates manual accounting of revenues. Taken together, narratives dispute the notion that smart metering aids in addressing operational challenges in the rural mini-grid environment. To avoid these unforeseen challenges, mini-grid operators need to consider the context-specific conditions that will influence their smart-metering setup's utility in order to minimize unintended consequences.

Second, the narratives indicate that mini-grid operators under-utilize the benefits of a smart-metering setup. Under-utilization implies inefficient use of scarce financial resources, as smart meters account for up to 40% of capital costs. Herein, inefficiency threatens the viability of mini-grid in low-income rural markets, as mini-grid operators often face considerable financial dilemmas when allocating scarce resources. Furthermore, although smart meters are considered crucial for the shift towards smart mini-grids, it is important to note that the successful implementation of smart metering requires thorough analysis and consideration during the planning phase. As the capacities of social enterprises are generally limited, the planning phase will aid mini-grid operators in evaluating smart metering alternatives. To this end, mini-grid operators could benefit from the criteria identified in the case study. The criteria present several functional aspects of a smart metering installation in rural settings. This functional view, presented as hierarchical criteria (see Table 3), counters the over-simplified representation of smart meters in the current mini-grid discourse.

In addition to the narrative analysis, the study establishes the usefulness of the MCDA method for identifying smart meters for mini-grid operations in rural areas. Concerning the social enterprise's decision problem to examine context-specific conditions, the MCDA approach has advantages over descriptive methods and field piloting. This case study demonstrates that selecting a smart-metering setup is a multi-criteria decision problem with varied and conflicting objectives. Given this decision problem, our approach illustrates the advantage of utilizing SMAA to evaluate different criteria associated with smart-metering installation in rural areas. Specifically, SMAA problem formulation emphasizes the importance of a hierarchy of different criteria to capture the dissimilarity of smart meters in terms of the characteristics, costs, specifications, and technologies.

9. Conclusions

The current article sets out to demonstrate the utility of SMAA to make informed decisions while selecting smart meters for mini-grids in rural areas. In addition to presenting the utility of the SMAA, the academic endeavor attempts to contextualize practitioners' experiences concerning smart meters use within mini-grid operations in rural areas using narrative analysis.

Against the above backdrop, the findings from this study offer new insights into smart-metering technologies and decision-making processes concerning mini-grid operations in rural areas. For mini-grid operators and policymakers, the qualitative interviews provide useful insights about unforeseen operational challenges associated with ground-level smart meter implementation. In conjunction with the narrative analysis, the SMAA results illustrate that decision-making surrounding smart metering ought to consider context-specific conditions. Moreover, to ensure efficient utilization of scarce resources, the experiences of the social enterprise indicate that mini-grid operators need to carefully evaluate smart meters in terms of multiple criteria. Herein, the hierarchy of criteria presented in this study could help mini-grid operators to comprehend the complexity associated with smart meter implementation in the purview of universal electrification of rural areas, especially the last mile. Finally, the current study fills the research gap by providing a systematic and theoretical analysis of smart meter selection in the energy planning literature for pre-feasibility, considering their capital-intensive nature in mini-grid operations.

This study was limited as it focused on a single company case study. While this allowed for a detailed analysis of one company, it weakened the general applicability of the obtained results. Therefore, future work should include a broader study that looks at smart meter usage on a practical level, considering and comparing different mini-grid companies.

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