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RESEARCH ARTICLE

Stakeholder Perspectives on Microgrid Interoperability in Energy Access

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ABSTRACT Interoperability is critical for the sustainability and scalability of decentralized energy systems. It facilitates self-coordination, component replacement, system expansion, upgrades, and integration with other systems, including the main grid. Despite its importance, achieving interoperability in the energy access sector remains a challenge, as stakeholders have diverse perspectives on approaches and strategies to achieve interoperability, creating further complexity. This study explores stakeholder perspectives on how microgrid interoperability can be achieved in the context of energy access, using Indonesia as a case study. To capture the diversity and subjectivity of expert opinions, the study employs the Q methodology, marking the first application of this method to the topic of interoperability. The study advances the theoretical understanding of interoperability in decentralized energy systems by revealing four distinct stakeholder perspectives, namely (1) Harmonization Promoters, (2) Industry Allies, (3) Tech Proponents, and (4) Public Advocates. Although there are some areas of consensus, stakeholders differ in their views on standardization, technical features, and stakeholder roles. These differences highlight the competing priorities that influence decision making on approaches to interoperability that balance technical, regulatory, and market considerations. This study provides practical insights for developing more inclusive and effective interoperability strategies, supported by empirical evidence derived from primary data gathered from relevant stakeholders.

INDEX TERMS Energy access, interoperability, microgrid, stakeholder perspective, Q methodology.

I. INTRODUCTION

In recent years, decentralized energy systems, such as off-grid solar and microgrids, have gained prominence as effective solutions for improving energy access in underserved regions. However, many of these systems were not originally designed for interoperability or system integration. Consequently, they often function as isolated standalone units that cannot be easily connected or communicated with other energy systems [1]. Whereas proprietary solutions may perform adequately within their specific operational context, they tend to create silos that hinder seamless integration with additional systems. This requires tailored integration and maintenance efforts, significantly increasing the complexity of the overall system architecture [2]. From the consumer's perspective, being locked into proprietary systems reduces flexibility, as they are restricted to using only specific appliances and cannot take advantage of other readily available options on the market [3].

The lack of interoperability has become a pressing concern as the deployment of solar technologies accelerates globally. Without the ability to effectively interconnect and coordinate,

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these systems face challenges in scaling up, ensuring long-term sustainability, and integrating into broader energy networks [4], [5]. Although standardization has often been proposed as the primary solution to interoperability [1], technical standards alone are not sufficient to fully address the issue [2], [6]. Efforts to improve interoperability must be guided by practical use cases and the concept of pragmatic interoperability, which emphasizes meaningful collaboration among systems that goes beyond mere data exchange [2], [7].

Addressing interoperability challenges involves more than just technical considerations. It also requires a shared understanding between stakeholders and an effective governance mechanism to support coordinated actions [1], [2], [4]. The ways in which various stakeholders—such as policymakers, technology providers, operators, and users—perceive and address interoperability barriers play a crucial role in shaping interoperability strategies [1]. However, there remains a limited understanding of how these diverse actors prioritize and implement strategies for developing interoperable energy solutions.

This knowledge gap presents a major obstacle to aligning the technological, operational, and regulatory dimensions essential for sustainable energy access. Addressing it requires a deeper understanding of the factors that influence interoperability.

This study aims to explore these dimensions by examining how stakeholder perspectives shape the path toward interoperable decentralized energy systems. The main objectives of this study are to:

- Investigate stakeholder views on challenges and opportunities associated with microgrid interoperability.
- Develop recommendations for practices that support interoperable microgrids for energy access.

The central research question in this study is "How do stakeholders perceive the challenges and strategies to achieve microgrid interoperability in the context of energy access?" By addressing this question, this study contributes to advancing theoretical understanding of energy system interoperability by incorporating subjective stakeholder viewpoints, which remain largely underexplored in the current energy access literature.

This research employs Q methodology, a structured approach that involves interviews with 24 stakeholders to investigate existing interoperability issues, examine strategies proposed in the literature, and explore how different stakeholders perceive these issues and potential strategies. The findings reveal polarized stakeholder perspectives influenced by competing priorities, suggesting the importance of participatory, inclusive, and transparent governance for interoperability.

A. LITERATURE REVIEW

The literature review examines the role of microgrids in energy access, especially in areas where extending the main electricity grid is impractical. It highlights the importance of interoperability in enabling the integration of diverse technologies and systems. The review then narrows its focus to Indonesia, analyzing the implementation of solar microgrids and the challenges posed by the country's archipelagic geography and rural electrification goals.

1) MICROGRID AS AN ENERGY ACCESS SOLUTION

Rural electrification programs to achieve universal access to energy have benefitted from decentralized energy technologies, such as microgrids powered by fossil fuels and renewable resources. These programs are primarily publicly funded by governments and donors, targeting communities in remote and underserved regions of countries in the Global South. Decentralized energy systems are particularly effective in areas where extending traditional grid infrastructure is not economically or technically feasible, especially in relatively congregated settlements [8].

In this study, microgrids are defined as power generation and distribution systems that supply a group of customers in unelectrified settlements. The capacity varies depending on the available resources and local energy demands, ranging from a few kilowatts to several megawatts. They can serve a small cluster of households as well as entire communities comprising several hundred houses [9]. Microgrids can operate independently (off-grid) or in conjunction with the main grid. The advancement of third-generation microgrids has significantly improved their ability to integrate renewable energy sources and interconnect with the central grid [8]. This capability is particularly beneficial in remote areas where the main grid is either absent or unreliable. Moreover, it facilitates the gradual expansion and scaling of microgrid systems, further improving energy access [10].

The deployment of microgrids faces challenges regarding their viability and sustainability. Their economic feasibility depends on innovative business models that can secure substantial initial investments and cover operational costs [10], [11]. Additionally, financial viability is heavily influenced by regulatory frameworks and the availability of public funding mechanisms, such as grants and subsidies [9], [11]. Beyond financial concerns, ensuring the sustainability of microgrids presents technical and institutional challenges. Long-term operation requires careful planning to address the increasing energy demand, grid integration, and scheduled replacement and refurbishment of key components [12], [13]. Operators and implementers must navigate these complexities to ensure the reliability of microgrid systems.

This study focuses on solar-powered microgrids installed in remote villages, which are typically established through public funding and later managed by the local community. To guide our analysis, we adopt the following definition of community microgrid: "a self-contained and self-sufficient local electricity supply system, either standalone or connected to a centralized grid of regional or national scale, comprising residential and other electric loads, and can be supported by high penetrations of local distributed renewables, other distributed energy and demand-side resources" [14]. Community microgrids are often viewed as a pre-electrification remedy, providing temporary access to electricity until the arrival of the main grid as demand grows. In some cases, such as isolated small islands, microgrids can serve as a long-term solution, provided that spare parts and repair services remain accessible. Solar microgrids can also complement other off-grid technologies, such as solar home systems and pico-lanterns. As the adoption of solar technologies expands, the market has seen a growing number of vendors offering a wide range of products, including solar panels, micro-inverters, and batteries. In all of these instances, interoperability issues are pertinent.

2) INTEROPERABILITY IN ENERGY ACCESS

Interoperability plays a crucial role in improving the reliability and scalability of microgrids and other decentralized energy systems [5], [15]. It addresses key operational challenges such as integrating multi-vendor equipment, enabling secure data exchange, and managing dynamic loads. Ensuring interoperability is essential for the effective functioning of decentralized energy systems, energy storage solutions, and management technologies [16], [17]. When microgrids are connected to the main grid, interoperability ensures effective communication and coordination between systems by aligning voltage, frequency, and control protocols. This not only ensures system stability, but also facilitates future upgrades and integration with broader energy networks.

Interoperability also simplifies maintenance and replacement. In the event of component failure or obsolescence, operators can source compatible parts from various vendors without compromising performance. This flexibility enables access to a wider range of spare parts, reducing the dependence on specific suppliers. Additionally, open interface specifications enable scalable system growth, making microgrids more adaptable to evolving energy needs [5].

Standards and guides from fields such as information technology and communications define interoperability as the ability of two or more networks, systems, devices, applications or components—whether from the same or different vendors—to securely and effectively exchange information, readily use that information, and cooperate to perform required functions accurately and efficiently [18], [19], [20], [21], [22]. Beyond information exchange, interoperability also encompasses operational compatibility. In a broader sense, interoperability can be defined as "a concept of using technology and standardization to enable systems, appliances, and devices to operate in the same environment and interact with no adverse effects. The interactions range from compatibility to exchanging information and using interchangeable components within systems" [4]. Among multiple definitions, several key features consistently highlighted in the literature are secure exchange, functionality, and vendor independence that allow systems to cooperate [23].

In a review paper on microgrid interoperability, Suryani et al. [1] categorized three levels of interoperability to address the shortcomings of the existing understanding of this concept, specifically in the context of energy access. They include interoperability between components and devices within a microgrid, between a microgrid and other decentralized energy technologies, and between a microgrid and the main grid through grid interconnection. The latter enables smooth transitions between grid-connected and islanded modes while ensuring technical and regulatory compliance.

The debate on interoperability revolves around how to balance market-driven innovation with the need for standardization, with the aim of ensuring affordability and quality while enabling the seamless integration of diverse energy systems [4], [22]. Key points of disagreement include trade-offs between customization and standardization, technical and engineering complexities, the division of responsibilities between government and the private sector, and how interoperability influences consumer choice [2], [3], [17].

Stakeholders expressed divergent views on the role of proprietary solutions. According to [2], proprietary technologies hinder the seamless integration of additional systems, which is a challenge frequently encountered in the context of energy access. Others argued that proprietary solutions are better at ensuring quality and security in energy systems.

An example of an initiative promoting interoperability in off-grid contexts is the Connect Initiative, launched by GOGLA, the global association for the off-grid solar energy industry. This effort aims to create a voluntary, standardized, and interoperable ecosystem for off-grid solar products. It focuses on defining universal connectors for 12V solar home system kits and appliances, aiming to enhance consumer flexibility and drive market growth [3]. The initiative envisions a market in which both interoperable and proprietary ecosystems can coexist and compete. This initiative tackles a segment within the broader interoperability ambition in the energy access sector.

3) SOLAR MICROGRIDS IN INDONESIA

Indonesia was selected as a case study due to its prominent utilization and development of microgrids for rural electrification. As an archipelagic nation comprising 13,558 islands—922 of which are permanently inhabited, according to the latest census [24]—Indonesia faces unique challenges in expanding energy access. The country's electrification efforts are primarily implemented by the National Utility Company (PLN), which currently operates 5,154 diesel power plants and 312 solar microgrids. These systems have a total installed capacity of 3,426 MW and 34 MW, respectively [25]. To reduce carbon emissions and reliance on diesel, PLN has launched an ambitious de-dieselization program aimed at gradually replacing 5,200 diesel power plants with renewable energy resources, gas-powered power plants, or integration with the national grid [26].

In addition to power plants built and operated by PLN, various rural electrification initiatives have been implemented by national and subnational governments, as well as international development organizations such as the World Bank and the United Nations Development Programme (UNDP). These programs have introduced a variety of technologies, including solar microgrids and pico-lanterns. However, tracking the exact number of systems deployed remains a challenge. According to the ESMAP database, Indonesia had installed 1,190 stand-alone microgrids by 2022, making it among the top ten countries with the highest number of microgrids [8]. The Indonesian government has continued rural electrification efforts, adding 35 solar microgrids in 2023 and 97 in 2024 [27], [28]. Additionally, UNDP Indonesia, through the ACCESS program, has built 22 solar microgrids in 21 villages, providing electricity to over 14,000 people [29]. Considering Indonesia's extensive deployment of solar technologies for electricity provision, the country offers an ideal context for studying stakeholder perspectives of interoperability.

B. STUDY CONTRIBUTIONS

This study offers several main contributions to the literature on microgrid interoperability. In terms of empirical contribution, the research provides systematic, empirical evidence through primary data that capture the views of real-world stakeholders in the sector.

In terms of methodological contribution, this is the first study applying the Q methodology to the topic of microgrid interoperability, offering a novel approach to exploring subjectivity in complex energy systems. The framework can be adapted for use in other regional or national contexts facing similar challenges in interoperability and energy access, making it a valuable reference for future interdisciplinary research.

The study advances the theoretical understanding of interoperability in decentralized energy systems by revealing four distinct stakeholder perspectives. These perspectives uncover the competing priorities that shape decision-making around standardization, governance, and technical integration, contributing to conceptualization of interoperability as a socio-technical issue.

Lastly, beyond technical dimensions, the study addresses operational practices and strategic policy considerations, offering actionable insights for policymakers and energy actors. By identifying consensus areas and key points of divergence, the findings can inform the design of more inclusive and context-sensitive strategies to enhance interoperability in decentralized energy systems.

C. ORGANIZATION OF THE PAPER

This article is structured into five main sections, each building on the previous to guide the reader through the research process and its findings. It begins with an *Introduction*, which outlines the rationale and motivation behind conducting the study. The *Literature Review* follows, providing an overview of the central themes. The *Methodology* section details the research design, data collection methods, analysis techniques, interpretation strategy, and validation procedures. In the *Results* section, the outcomes of the factor analysis are presented, highlighting the identification of four distinct perspectives. The *Discussions* offers a comparative analysis of these findings in relation to existing literature, highlighting key similarities and differences. Finally, the *Conclusion* synthesizes key insights drawn from theoretical frameworks and empirical results. A nomenclature table is provided in Appendix A (Table 8).

II. METHODOLOGY

A. GENERAL OVERVIEW OF Q METHODOLOGY

Q methodology study is an empirical work with exploratory focus. It was first introduced by William Stephenson in 1935 as an adaptation of factor analysis aiming to discover patterns of association between variables [30]. It applies a quantitative approach to investigate qualitative data, which in this case are the opinions of stakeholders [31]. It is one of the methods for openly and systematically examining human perspectives, which allows interactive participation of stakeholders to uncover individual perspectives thoroughly on a topic. It has also been proven to be a robust technique for analyzing the diversity of subjective perspectives [32].

Q methodological studies have two main features: gathering data in the form of Q sorts and analyzing these Q sorts using intercorrelation and by-person factor analysis [31]. A Q sort is the ranked arrangement of statements produced by a participant. Figure 1 illustrates how factor analysis works in Q methodology.

Q methodology has been applied to address "wicked problems"—complex issues involving multiple stakeholders with competing interests and priorities, each with different perspectives on the problem and its solutions [33], [34], [35], [36]. Díaz et al. [33] investigated potential conflicts among stakeholders in the implementation of renewable energy policy, identifying three perspectives based on different values and priorities across various levels of government in Switzerland. Mirkova and Padrón-Fumero [34] explored this in the context of just transitions in tourism-dependent island economies. Similarly, Haugen and Olaussen [35] used the Q methodology to study the sustainability of Norway's salmon farming industry, revealing two polarized views and two balanced opinions among stakeholders. In the Indonesian energy sector, the methodology has been applied to assess perspectives on carbon capture and storage technology as a means of reducing carbon emissions [36].

Universal energy access is yet another wicked problem [37], involving various stakeholders where solutions are not simply right-or-wrong, but rather fall along the spectrum of better-or-worse. Given its ability to navigate subjective complexities, the Q methodology is particularly suited to

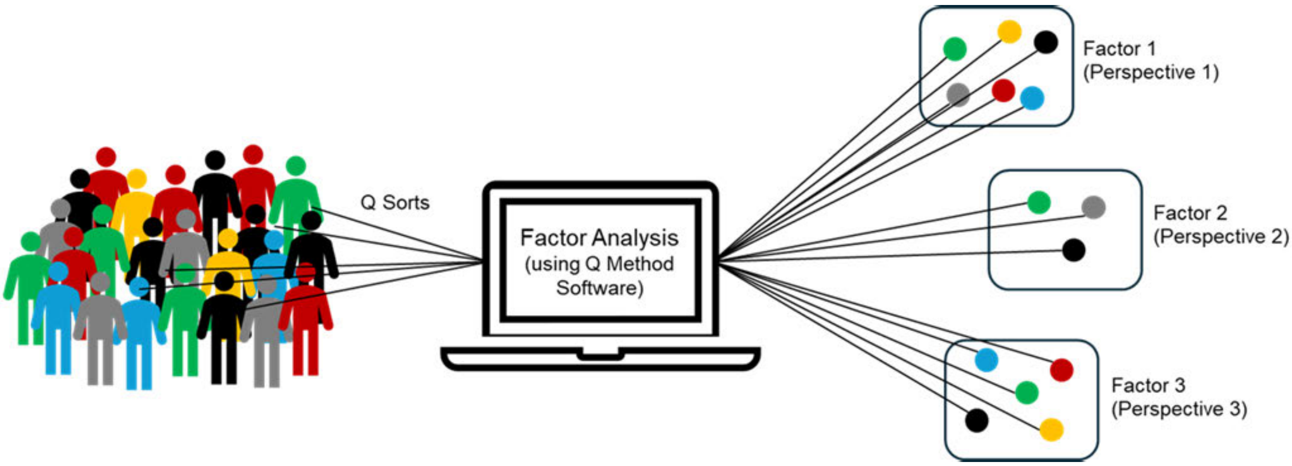

FIGURE 1. **Illustration of factor analysis in Q methodology. Adapted from [34].**

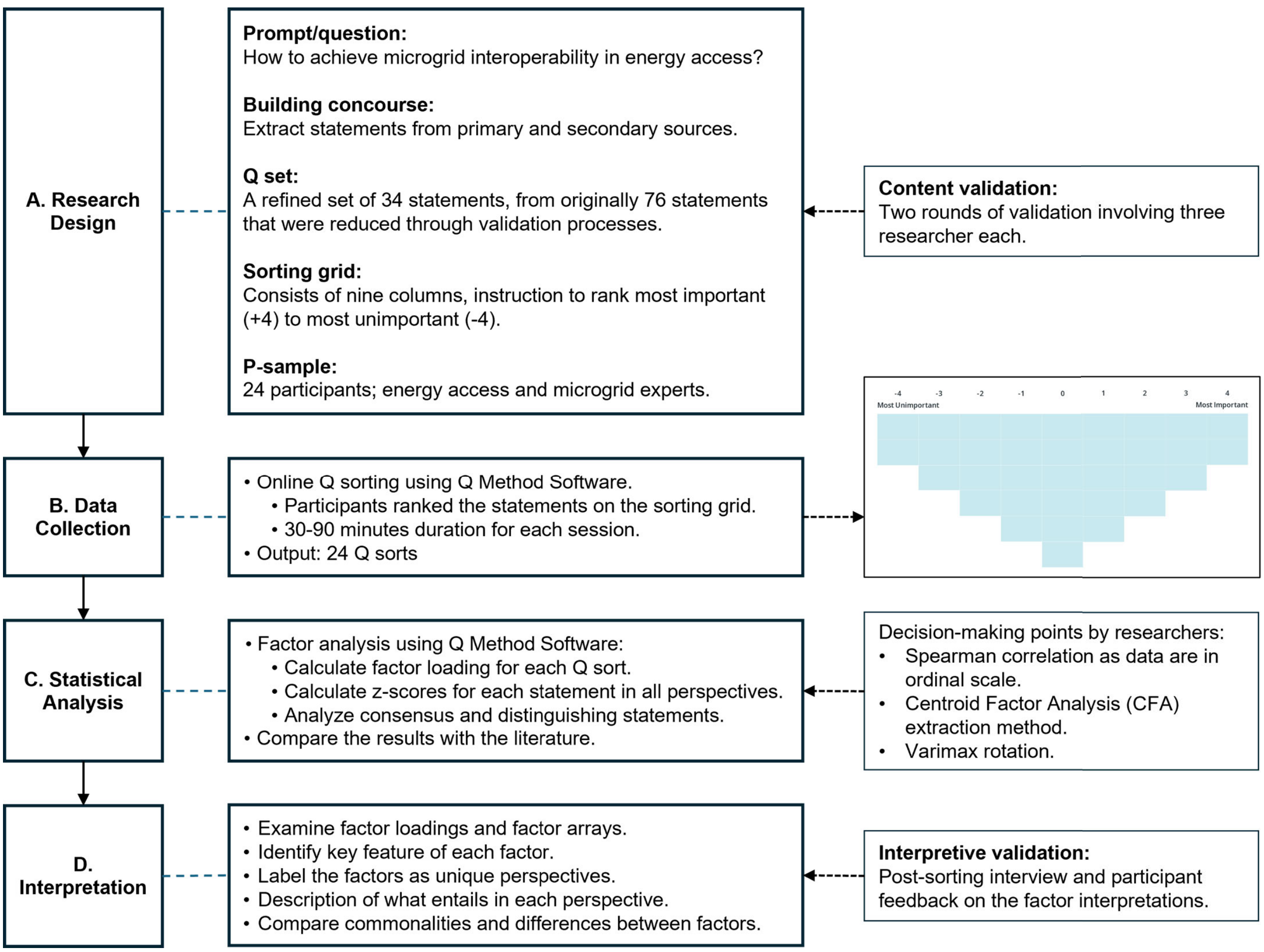

FIGURE 2. **Q methodology steps in this study. Adapted from [40].**

situations where multiple and diverse viewpoints must be considered. It can also be a valuable tool for evaluating stakeholder dialogues on wicked problems [38].

This study follows four stages sequentially: research design, data collection, statistical analysis, and interpretation [31], [39], [40], as shown in Figure 2.

B. RESEARCH DESIGN

Q methodology study begins with the development of concourse, which is a collection of statements pre-prepared by the authors. This statement set, known as Q set, was derived from the discourse on microgrid interoperability. Initial consultations with nine microgrid experts and practitioners in Indonesia revealed that the issue is relatively new and not yet largely discussed. Therefore, the concourse developed from these consultations was supplemented with the concourse presented in academic articles and technical reports. All secondary data were publicly available, while interview notes were anonymously documented.

The initial draft of the Q set comprises 76 statements selected from both primary and secondary sources. These statements were then refined through two validation rounds, each involving a group of three reviewers. All reviewers were researchers, and the coauthors of this article also took part in the validation process. The final Q set consists of 34 statements, covering four domains: technical feature, research and development (R&D), stakeholder role, and standardization (see Table 9 in Appendix B). These categories were intended as a reference for the researchers and were not disclosed to participants during the sorting and interviews.

Q methodology intends to identify existing viewpoints and then explain and compare them [41]. Its purpose is not to generalize the findings to a larger population [31], therefore having a large number of participants is not required. Instead, this research takes a strategic approach to select participants, based on their potential to provide vital, diverse, balanced, and insightful views on the topic. Participants (P-sample) were recruited by purposive sampling, which aimed to have stakeholders who jointly would present a variety of views on microgrid interoperability in the context of energy access. The selection criteria included profession, technical expertise, and years of experience with the subject matter. Nine respondents interviewed in the initial consultations were retained for the main study as no changes were made to the study materials. A total of 24 participants took part in the Q sorting step. To avoid homogeneity among participants, a balanced composition of three sectors—public, private, and academic—was maintained, as illustrated in Figure 3.

FIGURE 3. **Composition of P-sample.**

C. DATA COLLECTION

Interviews with the 24 participants were conducted by the first author between June and September 2023. During the interviews, participants performed a Q sorting task that involved rank-ordering a series of statements. The interviews were conducted online, and the Q sorting was performed using Q Method Software [42], which can be operated by the participants independently. Each participant received an introduction, an informed consent form, the Q set, instructions, and a sorting grid, all of which were accessible through the software.

At the beginning of the interview, participants were briefed about the objective of the study, the sorting process, and the intended use of the data. After providing informed consent, participants were guided to sort all 34 statements using a structured sorting grid. This grid follows an inverted normal distribution, ranging from +4 (most important) and −4 (most unimportant) (see Figure 4). Detailed instructions for the Q sorting procedure are available in the Supplementary Material. All participants gave permission for their interviews to be audio-recorded. At the end of the interview, they provided background information—off-the-record—on their academic qualifications, job roles, and years of experience via a questionnaire. Participation in the study was entirely voluntary, and no compensation was offered.

D. STATISTICAL ANALYSIS

The data collected from the Q sorting represent the scores given by each participant to each statement, ranging from +4 to −4. Each participant produces a unique Q sort, resulting in 24 Q sorts to be analyzed in this study. To draw common viewpoints from these Q sorts, a factor analysis was performed using Q Method Software.

The factor analysis aims to extract meaningful viewpoints by calculating and evaluating the correlation between Q sorts, following statistical methods. Spearman correlation was chosen for the analysis because the data are on an ordinal scale (ranked). Then, a factor extraction was performed to identify the shared pattern among the Q sorts. This is done statistically by evaluating the common variance. The factor extraction technique used in this study is the Centroid Factor Analysis (CFA), which allows the researcher to intervene instead of relying on a single mathematically best solution [31].

The first extracted factor indicates the largest portion of the common ground among participants, reflecting the strongest

-4	-3	-2	-1	0	1	2	3	4
Most unimportant								Most important
S4	S9	S32	S16	S22	S34	S14	S21	S31
S28	S30	S23	S13	S29	S25	S3	S17	S20
	S1	S5	S19	S12	S27	S7	S2	
		S18	S11	S6	S26	S33		
			S24	S10	S8			
				S15				

FIGURE 4. Example of a completed Q sort configuration.

shared points of view. The factor loadings were calculated to indicate how closely each Q sort aligned with the extracted factor. This process was repeated to extract all significant factors from the data.

Each factor consists of a set of statements, each given a specific score known as the z-score. A z-score is a weighted average of the values assigned to a statement by the Q sorts that are most closely associated with the factor [43]. Z scores are used to reconstruct the Q sort of a factor. The highest z-score corresponds to the highest rank (+4), indicating the most important statement, while the lowest negative value corresponds to the lowest rank (−4), indicating the least important statement.

Each factor contains distinguishing statements reflecting the difference between a statement's score across any two factors. When a statement's score on two factors exceeds this difference score, the statement is classified as a distinguishing statement [44], meaning that it highlights the unique characteristics of one perspective compared to another.

E. INTERPRETATION STRATEGY

The last step, arguably the most challenging step in Q Methodology, is interpreting each factor into distinct discourses. Each factor is generated as an idealized Q sort that represents a particular perspective. This critical step involves understanding and articulating the shared viewpoints (factors) that emerge from the initial Q sorts. The literature provides guidance on interpretation strategies [31], [40], which starts with examining factor loadings to identify which participants represent each factor. The factor arrays summarize how an ideal participant would rank the statements for each factor. The distinguishing statements highlight the unique perspective of each factor, whereas the consensus statements show areas of agreement between factors.

Based on factor arrays and distinguishing statements, a narrative or profile of each factor was developed. This was carried out by identifying the core values, key priorities, and the aspects that each perspective tend to downplay or overlook. The participant comments were revisited to provide additional context and clarify the ranking of certain statements. From the analysis, a descriptive label was assigned to each factor, reflecting on its central viewpoint. Finally, the findings were brought to the research context, positioning how these identified viewpoints engage with or challenge existing theories and discussions in the field.

F. VALIDATION

Q methodology is designed to explore subjective viewpoints of individuals rather than to assess objective correctness. Therefore, concerns about the validity of Q sorts do not directly apply [41], [44], [45]. To ensure the robustness and credibility of the results, this study implemented two validation measures. The first was content validation [46] during the concourse development phase. This involved two rounds of screening by separate groups of three researchers, followed by a pilot test with two additional researchers. The purpose of this process was to evaluate and refine the initial set of statements, condensing them into a manageable Q set suitable for the sorting by participants.

The second was an interpretive validation of the results derived from factor analysis. We achieved this by obtaining participant feedback on the factor interpretations to determine whether they recognized their own perspectives on the results. This step was intended to enhance the credibility of the interpretations. We also performed triangulation by comparing the findings with relevant studies and reports in the field.

To safeguard the transparency and consistency of the interpretive process, we provided a transparent trail to document how factor interpretations were developed. This process followed the crib-sheet technique introduced by [31], which provides a structured framework for analyzing each factor to ensure that no critical insights were overlooked. Each crib sheet includes four categories: statements with the highest rank (+4), statements with the lowest rank (−4), statements ranked higher than in any other factor, and statements ranked lower than in any other factor. The crib sheets for all four extracted factors are provided in the Supplementary Material.

TABLE 1. Four stakeholder perspectives based on four extracted factors.

Factor		1	2	3	4
General perspectives		The Harmonization Promoters	The Industry Allies	The Tech Proponents	The Public Advocates
Eigenvalues		4.62	1.82	1.76	1.36
Cumulative variance explained		19%	17%	34%	40%
Defining Q sorts		6	3	7	3
Stakeholder	Public	2	1	2	1
	Private	3	1	1	0
	Academic	1	1	4	2

TABLE 2. Factor arrays: Idealized Q sort values for each statement.

ID	Statement	P1	P2	P3	P4
S1	Microgrids should have the ability to connect with each other and share loads.	2	2	4	0
S2	Consumers can buy or sell appliances without being limited by system incompatibility.	-4	3	-3	2
S3	Plug-and-play solutions that work across a broad range of operating conditions are necessary.	0	-1	3	0
S4	Microgrids should have the ability to interconnect with the main grid.	0	-3	4	-3
S5	Communication between microgrids, consumers, operators, and the grid should be achieved.	3	-2	2	0
S6	Interoperability should allow replication and upscaling of microgrids.	0	2	2	-1
S7	Have the capability to externally exchange and readily use information securely and effectively.	-3	1	0	-1
S8	Make market requirements transparent and needs-driven.	-1	3	1	-3
S9	Physical compatibility should allow appliances from one vendor to be powered by systems from another.	-3	1	3	1
S10	Develop open-source technologies that can be used by various providers.	-2	-1	-2	-2
S11	Make more quantifiable data available to support the efforts to regulate interoperability.	-1	0	-1	4
S12	Conduct case studies highlighting successful implementations of microgrid interoperability.	2	-1	-1	-2
S13	Conduct consumer research to understand potential challenges to interoperability.	1	0	-1	0
S14	Gain more insight into the technical and economic aspects of interoperability.	1	-1	0	-1
S15	Continue R&D for hardware and software advances in interoperable solutions.	1	1	1	-1
S16	Establish common communication protocols to ensure full interoperability.	3	-2	2	2
S17	Use private sector alliances to define common specifications, achieve industry consensus for standards development.	2	2	-3	-4
S18	The microgrid sector comes together around a shared interoperability vision.	0	-3	0	-2
S19	A public entity can push a preferred approach through standardization and regulation.	-2	-4	-3	1
S20	Take a market-led approach for interoperability to progress naturally without external intervention.	-2	2	-4	-2
S21	The industry should lead by convening and building support for interoperable solutions among players.	-2	4	-4	-3
S22	Consensus among stakeholders to help the implementation of technical standards.	2	-1	-1	-4
S23	Implement consumer education to raise awareness of interoperability.	-1	-2	-1	0
S24	Create labeling to raise awareness of whether components are interoperable or not.	-3	-4	-2	-1
S25	Improve mechanisms for stakeholder collaboration to help the effort to regulate interoperability.	0	0	1	0
S26	Physical and communication interoperability should be governed by technical standards.	1	1	1	3
S27	Standards are key to creating interoperable infrastructure to build a complex grid of the future.	4	0	2	2
S28	Standards play a significant role in bringing technologies and interconnectivity requirements up to date.	3	-3	0	3
S29	Establish standards that define the appropriate security level.	4	-2	1	3
S30	Standards for interoperability should focus on power applications.	-4	1	-2	2
S31	Standards for interoperability should focus on information exchange, communications, and control.	1	3	3	4
S32	Standards should help make microgrids more user-friendly.	0	0	0	1
S33	Standardized components to allow providers benefit from economies of scale.	-1	0	-2	1
S34	Move away from proprietary solutions that may hamper interoperability.	-1	4	0	1

III. RESULTS

The findings of this study are presented in three subsections. First, we describe the factor extraction process used to identify distinct stakeholder perspectives. This is followed by a detailed interpretation of each perspective and an analysis of the areas of consensus and disagreement among them. A broader discussion of the results is provided in Section IV.

A. FACTOR EXTRACTION AND ANALYSIS

A total of 24 Q sorts were intercorrelated and factor-analyzed using Web-based Q Method Software [42]. Four factors were statistically extracted and rotated, which cumulatively explained 40% of the similarities between the Q sorts. Nineteen of the 24 Q sorts loaded significantly on one of these four factors. Each factor has an eigenvalue greater than 1 and at least three participants significantly load on it.

The perspectives were constructed as an interpretation of the four extracted factors, each representing a specific perspective on the subject matter. Table 1 summarizes the four factors and their respective general perspectives, eigenvalues, % of variance explained, and the defining Q sorts that load on a factor. The results suggest that Perspective 1 is strongly supported by private sector actors, while Perspective 3 is predominantly backed by academics. However, since each perspective is supported by various stakeholder groups, no conclusive evidence suggests that particular groups load significantly onto a specific perspective.

Table 2 presents the idealized ranking of each statement for the four extracted factors or perspectives (P1-P4).

TABLE 3. Perspectives on microgrid interoperability in energy access.

Factor	Factor 1	Factor 2	Factor 3	Factor 4
Perspective	**The Harmonization Promoters**	**The Industry Allies**	**The Tech Proponents**	**The Public Advocates**
Core Values	Collaborative, inclusive development and implementation of standards.	Industry-led and market-driven approaches to interoperability.	Technical design and solutions that enable interoperability.	Top-down regulation and formal technical standards driven by data.
Key Priorities	Forward-looking standards for future-oriented grid, cybersecurity considerations, inclusive stakeholder coordination	Open markets, private-sector alliances, non-proprietary solutions, consumer flexibility, minimal regulation.	Grid interconnectivity, load sharing, plug-and-play systems, technical compatibility, scalability and replicability.	Role of public authorities, structured technical standards, quantifiable data to justify regulation.
Downplay/ Less Priority	Overly rigid or narrow technical solutions, proprietary solutions, highly-technical framing	Government intervention, stakeholder consensus, regulation or top-down frameworks.	Market-led or industry-led approaches, open-sources focus, minimal governance.	Private sector alliances, stakeholder consensus in implementation of technical standards.

These rankings are based on z-scores, which represent the standardized value that indicates the strength of association between a statement and a given factor, calculated from the responses of participants who significantly loaded on that factor. The complete z-scores for each statement by factor are provided in Appendix C (Table 10).

B. PERSPECTIVE ANALYSIS

The interpretation process followed a structured sequence of steps, starting with the identification of statements with the highest and lowest rankings within each factor. Then, statements that were ranked higher or lower in one factor were compared to the others. By analyzing these rankings, we derived a comprehensive interpretation of the four perspectives. This involved a detailed comparison and contrast of how each perspective prioritize or downplay particular statements. Table 3 summarizes the core values and key priorities associated with each perspective and highlights the strategies for interoperability that were given less priority.

1) PERSPECTIVE 1: THE HARMONIZATION PROMOTERS

The first perspective reflects the predominant view among stakeholders and is built on six significantly loading Q sorts. It highlights the importance of electricity supply-side interventions through the development and adoption of interoperability standards (S27: 4). These standards are critical in harmonizing technologies and fostering interconnectivity. Rather than focusing on physical compatibility, the emphasis is on establishing universal communication protocols to ensure full interoperability (S16: 3), while simultaneously safeguarding security measures (S29: 4). This approach spans beyond microgrid systems, facilitating seamless connectivity between microgrids, consumers, operators, and the larger grid (S5: 3). Collaboration within the microgrid sector—especially through private-sector alliances—is essential for encouraging industry consensus and driving standard development (S17, S22: 2).

Regarding R&D, this perspective identifies the lack of understanding of interoperability as a major impediment. Therefore, it advocates for case studies on successful microgrid interoperability to improve awareness of its benefits (S12: 2). Consumer research is also deemed important in identifying potential interoperability challenges on the demand side (S13: 1). Unlike the other three perspectives, the Harmonization Promoter perceives studies on the technical and economic aspects of interoperability as necessary (S14: 1). For instance, examining issues such as mismatches due to proprietary connectors and adapters can prevent seamless operation, while analyzing the impact of vendor lock-in can shed light on how it drives up costs for businesses trying to integrate new software.

This perspective does not focus on defining interoperability itself. Rather, it asserts that interoperability is not simply a choice between physical or communication compatibility, although it leans toward communication standards as the more important approach than physical interoperability (S9: −3). Furthermore, it argues that consumers' ability to choose appliances should not be the primary concern (S2: −4). While open-source technologies can help achieve interoperability, they are not seen as the key solution in this perspective (S10: −2). Instead, it prioritizes stakeholder consensus in implementing technical standards.

The insights from Perspective 1 align with the view that the core challenges to interoperability stem from the need for standardization [1] and effective governance mechanisms [2], [6]. This perspective is characterized by eight distinguishing statements that define its unique stance (Table 4).

2) PERSPECTIVE 2: THE INDUSTRY ALLIES

This perspective highlights the industry's critical role in advocating interoperable solutions (S21: 4). It supports a shift from proprietary to more adaptable solutions (S34: 4), fostering a dynamic market that is needs-driven (S8: 3), where consumers have greater freedom to choose the products they prefer (S2: 3). Rather than relying on public entities, this perspective emphasizes private-sector alliances as the key to defining common specifications and driving standard development. A notable example of industry alliance is the USB Implementers Forum, where technology companies formed a corporation to establish universal charging and data

TABLE 4. Distinguishing statements for Perspective 1.

S	Statement	Z-Score	Rank
27	Standards are key to creating interoperable infrastructure to build a complex grid of the future.	2.22604	4
12	Conduct case studies highlighting successful implementations of microgrid interoperability.	1.04324	2
22	Consensus among stakeholders to help the implementation of technical standards.	0.91496	2
14	Gain more insight into the technical and economic aspects of interoperability.	0.46842	1
4	Microgrids should have the ability to interconnect with the main grid	0.19568	0
7	Have the capability to externally exchange and readily use information securely and effectively.	-1.15198	-3
9	Physical compatibility should allow appliances from one vendor to be powered by systems from another.	-1.16747	-3
30	Standards for interoperability should focus on power applications.	-1.73508	-4

transfer standards. The stakeholders in this group envision the microgrid sector adopting a market-led approach that allows interoperability to progress naturally without external intervention (S20: 2). In this context, external intervention refers to any influence, regulations, or directives imposed by entities outside the microgrid industry, such as national or local government mandates (S19: −4) and involvements from non-industry stakeholders such as non-governmental organizations (NGOs).

Aligned with Perspectives 1 and 3, the stakeholders in this group support R&D efforts geared toward enhancing hardware and software capabilities to facilitate interoperability (S15: 1). But they downplay the need for deeper insight into the technical and economic aspects of interoperability (S14: −1). Technically, the priority is on secure and effective external information exchange (S7: 1), aiming for microgrid solutions that are replicable and scalable (S6: 2). However, this perspective overlooks the importance of consumer education in raising awareness of interoperability (S23: −2, S24: −4). This contradicts the recommendations for labeling and consumer education to help users identify whether components are interoperable [4]. Without proper understanding, for example, a user might purchase a device that is incompatible with their existing system.

This perspective differs significantly from Perspective 1, expressing skepticism about the effectiveness of standards in achieving interoperability. While all stakeholders generally agree that interoperability involves balancing physical and communication compatibility (S26: 1), they disagree on the role of standards in bringing technologies and interconnectivity requirements up to date (S28: −3). Unlike the other three perspectives, this group does not prioritize plug-and-play solutions as an important goal of interoperability (S3: −1) and rejects the idea that interoperability is mainly about interconnecting microgrids to the main grid (S4: −3).

TABLE 5. Distinguishing statements for perspective 2.

S	Statement	Z-Score	Rank
21	The industry should lead by convening and building support for interoperable solutions among players.	2.16414	4
34	Move away from proprietary solutions that may hamper interoperability.	1.63576	4
8	Make market requirements transparent and needs-driven.	1.40023	3
20	Take a market-led approach for interoperability to progress naturally without external intervention.	1.05677	2
5	Communication between microgrids, consumers, operators, and the grid should be achieved.	-0.77343	-2
16	Establish common communication protocols to ensure full interoperability.	-0.87204	-2
29	Establish standards that define the appropriate security level.	-1.01828	-2
28	Standards play a significant role in bringing technologies and interconnectivity requirements up to date.	-1.02819	-3
24	Create labeling to raise awareness of whether components are interoperable or not.	-1.8808	-4

Moreover, a shared vision for interoperability within the microgrid sector is not considered essential (S18: −3).

The insights from Perspective 2 reflect the significant role that the industry plays in advancing efforts to achieve interoperability [3], [4]. This perspective is defined by nine distinguishing statements that highlight its unique viewpoint (Table 5).

3) PERSPECTIVE 3: THE TECH PROPONENTS

This perspective underlines the importance of technical features to ensure interoperability in microgrids. They focus on what must be achieved rather than how to achieve it. Above all, microgrids must have the ability to connect and share loads (S1: 4), allowing replication and upscaling (S6: 2) to support their growth. In contrast to the other perspectives, the Tech Proponent views the interconnection of microgrids to the main grid as essential for broader system integration (S1: 4). Plug-and-play capability is favored, promoting solutions that can function effectively across diverse operating conditions (S3: 3), such as variation in voltage (110V vs. 230V) and frequency (50 Hz vs. 60 Hz). For example, many modern electronic devices are designed with dual-voltage capabilities, allowing them to automatically adjust to different voltages. Physical compatibility is emphasized, particularly in voltage standards and connector alignment, so that appliances from different vendors can operate smoothly on various systems (S9: 3).

Two approaches to interoperability stand out in this perspective, relative to the other three perspectives. They are: continued R&D efforts in hardware and software to advance interoperable solutions (S15: 1) and stakeholder collaboration mechanisms to effectively regulate and govern interoperability (S25: 1). However, this perspective is cautious

TABLE 6. Distinguishing statements for perspective 3.

S	Statement	Z-Score	Rank
4	Microgrids should have the ability to interconnect with the main grid.	2.57197	4
1	Microgrids should have the ability to connect with each other and share loads.	2.28161	4
9	Physical compatibility should allow appliances from one vendor to be powered by systems from another.	1.53865	3
3	Plug-and-play solutions that work across a broad range of operating conditions are necessary.	1.08059	3
29	Establish standards that define the appropriate security level.	0.35515	1
8	Make market requirements transparent and needs-driven.	0.32706	1
28	Standards play a significant role in bringing technologies and interconnectivity requirements up to date.	-0.22664	0
30	Standards for interoperability should focus on power applications.	-0.8167	-2
17	Use private sector alliances to define common specifications, achieve industry consensus for standards development.	-1.15498	-3
20	Take a market-led approach that allows interoperability to progress naturally without external intervention.	-2.12308	-4

TABLE 7. Distinguishing statements for perspective 4.

S	Statement	Z-Score	Rank
11	Make more quantifiable data available to support the efforts to regulate interoperability.	1.62494	4
26	Physical and communication interoperability should be governed by technical standards.	1.62004	3
34	Move away from proprietary solutions that may hamper interoperability.	0.44144	1
19	A public entity can push a preferred approach through standardization and regulation.	0.33292	1
1	Microgrids should have the ability to connect with each other and share loads.	-0.0468	0
15	The microgrid sector should continue R&D for hardware and software advances in interoperable solutions.	-0.38462	-1
22	Consensus among stakeholders to help the implementation of technical standards.	-1.80989	-1
17	Use private sector alliances to define common specifications, achieve industry consensus, and lay the groundwork for standards development.	-1.8197	-4

about certain approaches. While open-source technologies are recognized for their potential to improve microgrids accessibility [4], they are not seen as a primary focus (S10: −2).

The perspective generally ranked standardization lower relative to the other perspectives (S26-S34), except for acknowledging the importance of standards for information exchange, communications, and control (S31: 3). As an example, despite the strong support for microgrid interconnection with the main grid (S4: 4), this perspective ranked low importance on standardization in power applications (S30: −2). In this context, power application refers to the type of electrical power usage and interconnection when integrating distributed energy resources into the main grid [5]. Furthermore, this perspective does not prioritize any specific stakeholder in driving interoperability. This is reflected in its low ranking regarding the roles of industry (S20: −4), public entity (S19: −3), and private-sector alliances (S17: −3).

Perspective 3 emphasizes the critical importance of technical factors in achieving interoperability. It strongly supports the view in the literature that plug-and-play capability is essential. Ten distinguishing statements define how Perspective 3 differs from the others (Table 6).

4) PERSPECTIVE 4: THE PUBLIC ADVOCATES

This perspective favors preserving existing structures, implied by a low priority in innovative technical and institutional solutions for interoperability. While they support technical standards to govern both physical and communication interoperability (S26: 3), they do not provide clear ideas on how interoperability should look like. Their emphasis is on making quantifiable data readily available to support regulatory efforts (S11: 4), a key distinction from the other perspectives. They view standards as essential for updating technologies and ensuring that interconnectivity requirements evolve in line with the sector's needs (S28: 3). They advocate for public-driven standardization and formal regulation (S19: 1).

In contrast to the Tech Proponent, the stakeholders in this group shift away from technical complexities. It does not prioritize microgrid interconnection and load-sharing capabilities (S1: 0) and does not consider interconnecting microgrids to the main grid a priority (S4: −3). The potential of interoperability in replicating and scaling microgrids is considered less critical (S6: −1). Instead, this group values consumer flexibility to buy and sell appliances without being restricted by system incompatibility (S2: 2). Unlike the other three perspectives, the Public Advocates includes consumer awareness under consideration (S23: 0) and suggests consumer education initiatives to improve understanding of interoperability. Moreover, this perspective recognizes the role for public entities in promoting standardization and regulation (S19: 1), ranking it higher than the other perspective.

The ranking pattern of this group indicates less emphasis on technical aspects and expressed skepticism toward private-sector alliances as a foundation for standards development (S17: −4). Likewise, they do not consider stakeholder consensus important for implementing technical standards (S22: −4). Eight distinguishing statements define how Perspective 4 differs from the previous three perspectives (Table 7).

C. CONSENSUS AND DISAGREEMENT

A comparative examination of how the four perspectives align or diverge is presented here. The central question posed

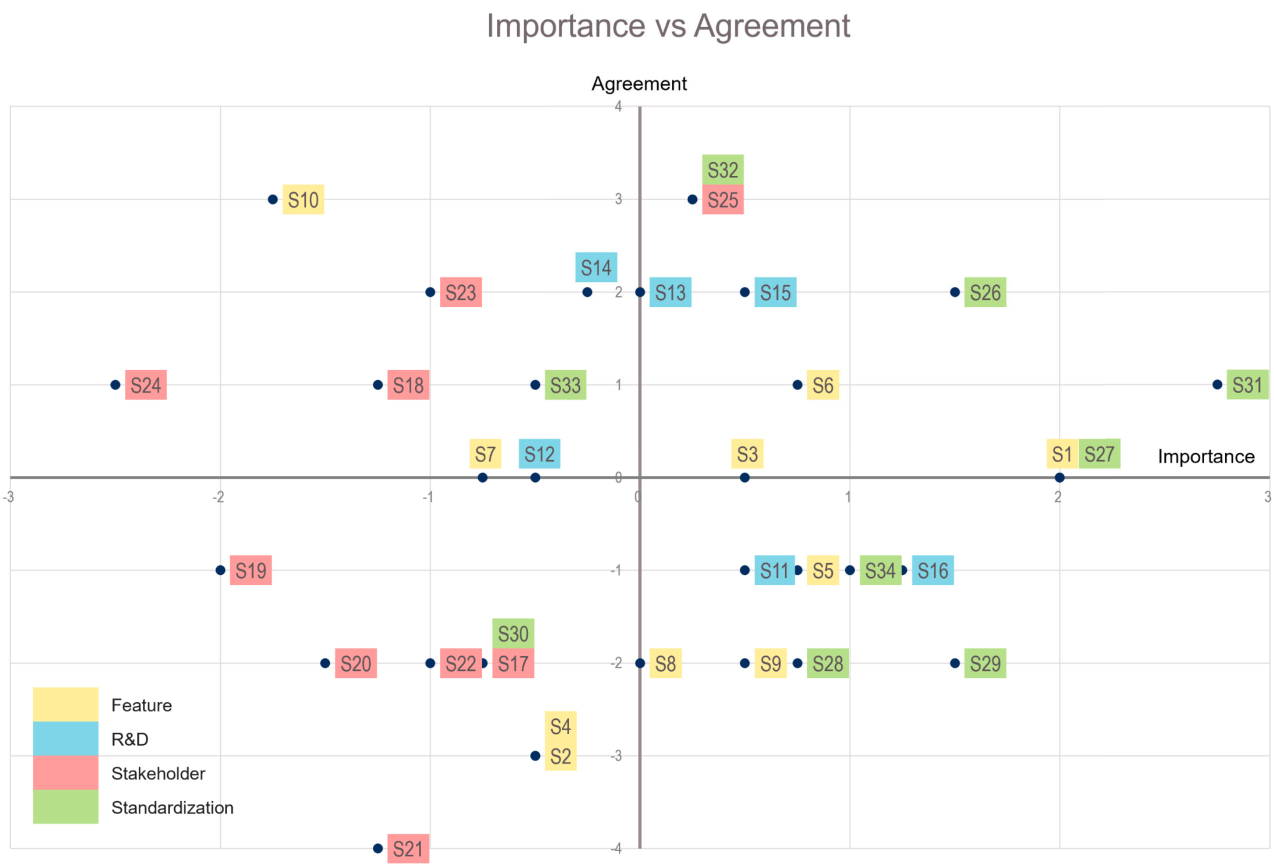

FIGURE 5. **Importance of strategies and agreement between perspectives.**

to the study participants during the sorting task was to identify the most effective strategies for achieving microgrid interoperability. Participants were instructed to keep this objective in mind when assigning a rank to each statement. In addition to evaluating the importance of strategies, we also explored the degree of agreement or disagreement between perspectives on which strategies are considered most critical. This is done by analyzing statements that generated strong consensus (high agreement) or conflict (low agreement). Figure 5 illustrates the relationship between the importance of strategies and the level of agreement among four stakeholder perspectives.

A systematic review on microgrid interoperability highlights standardization as a dominant strategy proposed in the literature [1]. This is reflected in our findings, where statements related to standardization received relatively high ranking (S31, S27, S1, S26, S29). The one exception to this trend was S1, which did not emphasize standards but rather the technical feature of interoperability, where microgrids should be able to interconnect and share loads seamlessly. There was general agreement among perspectives regarding the importance of these five strategies. However, one point of deviation was shown (S29), where stakeholders expressed varying levels of concern over the importance of security measures. In particular, Perspectives 1 (Harmonization Promoters) and 4 (Public Advocates) view security as a critical factor to prioritize, in contrast to Perspective 2 (Industry Allies), which placed low emphasis on this issue. Most participants perceived security issues as those related to cybersecurity, data integrity and privacy. Security concerns also extend to illegal connections, which are common in remote villages [13]. These illegal connections can compromise system integrity and cause financial losses due to unauthorized consumption and reduced revenue.

The study also identified strategies that the participants deemed less important relative to others (S24, S19, S10, S20). Participants considered product labeling to raise awareness about component interoperability (S24) as a ‘‘nice-to-have’’ rather than a ‘‘must-have’’ strategy. Although it could offer some benefits, it was not considered a highly effective means of interoperability. Similarly, except for Perspective 4 (Public Advocates), there was a broad agreement that the involvement of public sector entities to push standardization and regulation (S19) was not seen as an effective way to achieve interoperability. Many stakeholders felt that such top-down approaches did not account for the fast-paced development of microgrid

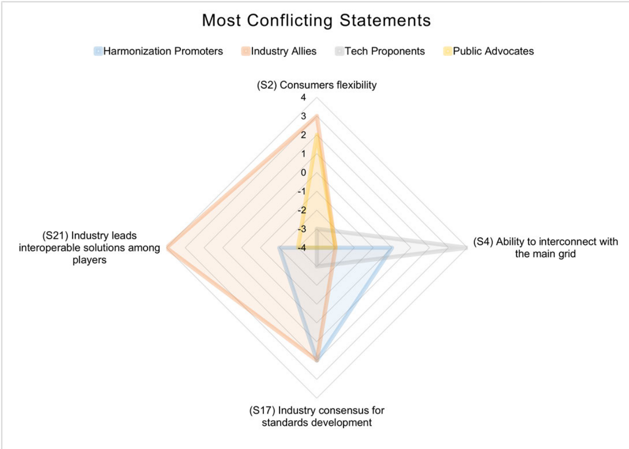

FIGURE 6. Most conflicting statements.

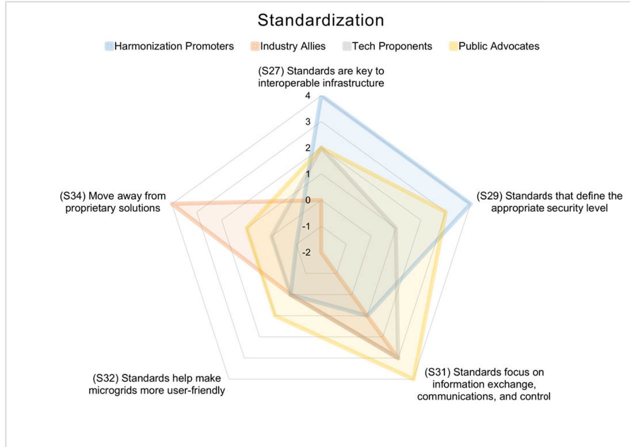

FIGURE 7. Perspective on standardization.

technologies. Moreover, a particularly distinct viewpoint was expressed in Perspective 2 (Industry Allies), which differed on the role of market and industry in driving interoperability (S20).

The stakeholders show significant disagreements in several areas, including technical features (S2, S4) and stakeholder roles (S17, S21), as shown in Figure 6. Regarding consumer flexibility in choosing components or appliances, Perspective 2 (Industry Allies) places the highest importance compared to the others. This aligns with the industry's role in promoting interoperable systems in the market [2], [3], [4]. It reflects the importance of enabling consumers to purchase off-grid solar products or allowing microgrid operators to source replacement components independently. Only Perspective 3 (Tech Proponents) considers the ability to interconnect with the grid a top priority of an interoperable energy system. This feature is particularly relevant in the development of smart grid infrastructure [5].

IV. DISCUSSION

A. STANDARDIZATION APPROACH

The emphasis on standardization reflects a shared understanding that standardized frameworks, along with detailed system specifications and rigorous testing procedures, are essential to achieving interoperability [5], [47]. As shown in Figure 7, all four perspectives generally recognized standards as a key strategy. Trivedi et al. [5] argue that a standardization-driven approach offers significant benefits over proprietary solutions, particularly in mitigating the risks associated with vendor lock-in. Perspective 2 (Industry Allies) strongly supports this view, emphasizing the importance of strengthening communication standards.

Proprietary solutions, while potentially offering benefits such as tailored solutions, can restrict flexibility and limit integration with other systems. In contrast, adopting standards ensures that devices and systems from different vendors can interoperate directly, facilitated by gateway technologies such as communication protocols [48], [49], [50]. Therefore, standardization promotes scalability and reduces dependency on single-vendor solutions.

B. TECHNICAL FEATURES

The findings on several interoperability features reveal conflicting views, particularly regarding plug-and-play solutions (S3) and open source technologies (S10), as shown in Figure 8. This study finds that only stakeholders aligned with Perspective 3 (Tech Proponents) consider plug-and-play capability (S3) high priority as they view seamless, ready-to-use connectivity as a core feature of interoperability. This view aligns with the existing literature, which positions plug-and-play capability as the highest maturity level of interoperability [2], [4]. Schütz et al. [2] argue that plug-and-play mechanisms are indispensable, particularly in managing the unpredictable inclusion of heterogeneous systems. Although their work focuses on smart grid contexts, the same challenge is relevant in energy access settings.

There is a broad consensus across all four perspectives that developing open-source technologies (S10) is not a priority, as reflected in the consistently low rankings. This contrasts to the literature that advocates an open systems approach as a means to reduce the risk of vendor lock-in associated with proprietary solutions [3], [5].

Regarding grid interconnectivity, stakeholders aligned with Perspective 3 (Tech Proponents) argue that interoperability should enable microgrids to interconnect with the main grid. In contrast, stakeholders associated with Perspectives 2 (Industry Allies) and 4 (Public Advocates) do not consider this an essential requirement. Instead, they prioritize other factors, such as ensuring consumer flexibility to buy or sell appliances without being constrained by system incompatibility (S2).

The differing views on the technical features of interoperability indicate a fundamental divide in how stakeholders perceive the concept itself.

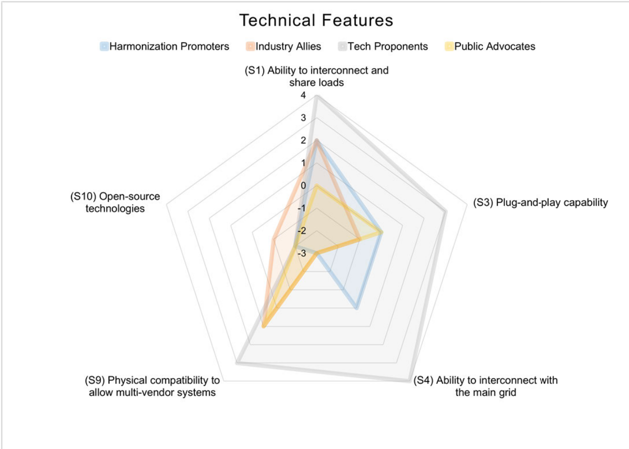

FIGURE 8. Perspective on technical features.

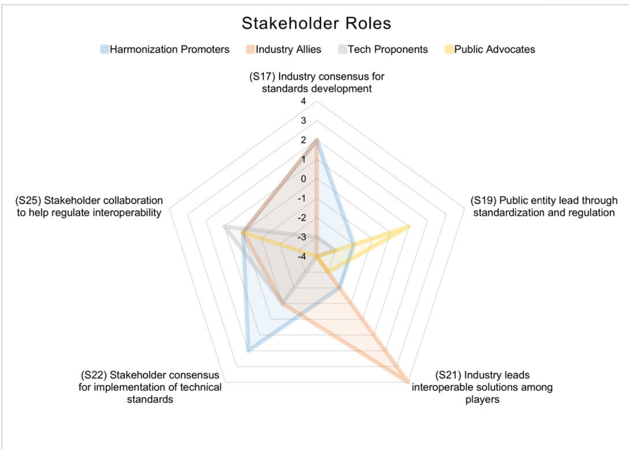

FIGURE 9. Perspectives on stakeholder roles.

C. STAKEHOLDER ROLES

Interoperability extends beyond meeting technical requirements. Challenges often arise during the adaptation and implementation of technological solutions. This is where the stakeholders play a pivotal role. Their needs and roles should guide the development of interoperable systems, ensuring that technical and societal requirements are integrated into energy system architectures [17].

This study systematically reveals the varying stakeholder perspectives on how to address interoperability. A key point of divergence is who should lead these efforts; the industry or public authorities, as shown in Figure 9. Supporters of an industry-led approach (Perspective 2) argue that the industry is better positioned to understand technological advances and constraints. Schütz et al. [2] propose a community-based approach, where actors involved in specific use cases drive the efforts based on shared industrial interests. This model aligns closely with Perspective 2. In contrast, supporters of public-led approach emphasize that energy access is predominantly driven by the public sector. Therefore, they argue that interoperability should be achieved through formal standardization and regulatory frameworks.

TABLE 8. Technical, methodological, and context-specific terms.

Interoperability	The ability of systems or components to work together across technical boundaries.
Microgrid	A power generation and distribution system for a group of customers in unelectrified settlements.
Plug-and-play	A feature of systems that are easily installed and function with minimal configuration.
CFA	Centroid Factor Analysis.
Concourse	The full collection of possible statements about a topic.
Factor analysis	A statistical method to identify shared patterns of opinion in Q methodology.
Factor arrays	An idealized or composite Q sort that represent each factor, used to interpret each perspective.
Factor loading	An indication of how closely a participant's Q sort correlates with the extracted factors.
P-sample	A group of research participants performing Q sorting.
Q methodology	A research method for studying people's subjectivity.
Q set	A refined representative set of statements from the concourse for participants to sort.
Q sort	The core data contains the ranked statements produced by participants.
Q sorting	The process where participants rank the Q set along a distribution grid.
Varimax rotation	A method to make each Q sort load highly to one factor and minimally on others by maximizing the variance of squared loadings.
Z-score	A standardized score that indicates how strongly a statement is associated with a factor, based on all participants who significantly load on that factor.
EPC	Engineering, Procurement, and Construction.
ESMAP	Energy Sector Management Assistance Program.
IPP	Independent Power Producer.
NGO	Non-Governmental Organization.
PLN	Perusahaan Listrik Negara – Indonesia's state-owned electricity company.
R&D	Research and Development.
RUPTL	Indonesia's Electricity Supply Business Plan.
SDG 7	UN Goal for access to affordable, reliable, and sustainable energy for all.
UNDP	United Nations Development Programme.

D. LIMITATIONS AND FUTURE RESEARCH

As a method to analyze subjectivity, the Q methodology has several limitations. A primary concern is the risk of researcher bias throughout the study stages, from research design to interpretation. Bias can arise in decisions regarding the development of concourses, i.e., the collection of statements, as well as in the interpretation of the extracted factors. Another limitation stems from participant selection, as they were chosen based on specific criteria, including technical or engineering background, under the assumption that they would be more familiar with the topic of interoperability. This approach may overlook perspectives from non-technical stakeholders who might offer different insights on the topic.

TABLE 9. Statements in the concourse with corresponding themes.

ID	Statement	Theme
S1	Microgrids should have the ability to connect with each other and share loads.	Feature
S2	Consumers can buy or sell appliances without being limited by system incompatibility.	Feature
S3	Plug-and-play solutions that work across a broad range of operating conditions are necessary.	Feature
S4	Microgrids should have the ability to interconnect with the main grid.	Feature
S5	Communication between microgrids, consumers, operators, and the grid should be achieved.	Feature
S6	Interoperability should allow replication and upscaling of microgrids.	Feature
S7	Have the capability to externally exchange and readily use information securely and effectively.	Feature
S8	Make market requirements transparent and needs-driven.	Feature
S9	Physical compatibility should allow appliances from one vendor to be powered by systems from another.	Feature
S10	Develop open-source technologies that can be used by various providers.	Feature
S11	Make more quantifiable data available to support the efforts to regulate interoperability.	R&D
S12	Conduct case studies highlighting successful implementations of microgrid interoperability.	R&D
S13	Conduct consumer research to understand potential challenges to interoperability.	R&D
S14	Gain more insight into the technical and economic aspects of interoperability.	R&D
S15	Continue R&D for hardware and software advances in interoperable solutions.	R&D
S16	Establish common communication protocols to ensure full interoperability.	R&D
S17	Use private sector alliances to define common specifications, achieve industry consensus for standards development.	Stakeholder
S18	The microgrid sector comes together around a shared interoperability vision.	Stakeholder
S19	A public entity can push a preferred approach through standardization and regulation.	Stakeholder
S20	Take a market-led approach that allows interoperability to progress naturally without external intervention.	Stakeholder
S21	The industry should lead by convening and building support for interoperable solutions among players.	Stakeholder
S22	Consensus among stakeholders to help the implementation of technical standards.	Stakeholder
S23	Implement consumer education to raise awareness of interoperability.	Stakeholder
S24	Create labeling to raise awareness of whether components are interoperable or not.	Stakeholder
S25	Improve mechanisms for stakeholder collaboration to help the effort to regulate interoperability.	Stakeholder
S26	Physical and communication interoperability should be governed by technical standards.	Standardization
S27	Standards are key to creating interoperable infrastructure to build a complex grid of the future.	Standardization
S28	Standards play a significant role in bringing technologies and interconnectivity requirements up to date.	Standardization
S29	Establish standards that define the appropriate security level.	Standardization
S30	Standards for interoperability should focus on power applications.	Standardization
S31	Standards for interoperability should focus on information exchange, communications, and control.	Standardization
S32	Standards should help make microgrids more user-friendly.	Standardization
S33	Standardized components to allow providers benefit from economies of scale.	Standardization
S34	Move away from proprietary solutions that may hamper interoperability.	Standardization

Additionally, the use of a single-country case study also presents a limitation, as interoperability is a global and highly technical issue, with many relevant technologies originating outside the studied country.

To mitigate bias, several measures were employed in this study. First, both primary and secondary data were used to build the concourse or Q set, ensuring a broader and more diverse representation of perspectives. Additionally, two layers of statement validation process were implemented, involving researchers who were not co-authors of this paper. Second, the P-sample (research participants) was anonymized using coded identifiers. This helps maintain the anonymity of participants during analysis. Third, the interpretation of the extracted factors was carefully discussed among all co-authors to ensure that the meanings assigned to each factor were aligned with the statistical analysis and adequately reflective of the data.

Despite these efforts, it is likely that the Q set used in this study did not cover the full range of possible issues related to microgrid interoperability. There is also the possibility that researcher bias affected the selection, formulation, and structure of the statements included in the Q set. Future research can benefit from adopting an even more rigorous and systematic approach in concourse development, as this phase is critical for ensuring comprehensive coverage of the topic. Expanding the scope to include a different set of participants and comparative case studies from different countries could further strengthen the analysis. The authors believe that conducting more Q studies will improve the reliability of the results and the interpretation derived from the analysis. Furthermore, case studies highlighting successful real-world implementation of interoperability in decentralized energy system would offer valuable contributions to existing literature.

V. CONCLUSION

This study marks the first-ever exploration of stakeholder perspectives on microgrid interoperability in the context of energy access. It is also the first application of the Q methodology on this topic. The findings reveal a diverse range of viewpoints, offering insights into how different stakeholders perceive and prioritize strategies to enhance interoperability in energy access.

Four distinct perspectives drawn from the analysis, reflecting opinions of various stakeholders. The first emphasizes the necessity of harmonization through interoperability standards, requiring extensive collaboration and mutual understanding among stakeholders during their development

TABLE 10. Factor ranks and z-scores of Q sorts that define each factor.

ID	Factor 1		Factor 2		Factor 3		Factor 4	
	Rank	Z-Score	Rank	Z-Score	Rank	Z-Score	Rank	Z-Score
S1	2	0.96926	2	0.82404	4	2.28161	0	-0.0468
S2	-4	-1.50176	3	1.14586	-3	-1.04207	2	0.89248
S3	0	-0.29358	-1	-0.47085	3	1.08059	0	0.15286
S4	0	0.19568	-3	-1.30181	4	2.57197	-3	-1.67174
S5	3	1.07652	-2	-0.77343	2	0.88712	0	0.24668
S6	0	0.13801	2	1.00876	2	0.87648	-1	-0.38952
S7	-3	-1.15198	1	0.23571	0	0.25133	-1	-0.32801
S8	-1	-0.72052	3	1.40023	1	0.32706	-3	-1.35865
S9	-3	-1.16747	1	0.33394	3	1.53865	1	0.69281
S10	-2	-0.96044	-1	-0.49962	-2	-0.57731	-2	-1.16388
S11	-1	-0.78955	0	0.10814	-1	-0.39463	4	1.62494
S12	2	1.04324	-1	-0.50914	-1	-0.4298	-2	-0.64111
S13	1	0.24608	0	-0.41053	-1	-0.55953	0	-0.13304
S14	1	0.46842	-1	-0.4899	0	-0.16398	-1	-0.5894
S15	1	0.37124	1	0.49962	1	0.30135	-1	-0.38462
S16	3	1.40482	-2	-0.87204	2	0.8241	2	0.99364
S17	2	0.97233	2	0.91986	-3	-1.15498	-4	-1.8197
S18	0	-0.06172	-3	-1.27305	0	-0.34931	-2	-0.83587
S19	-2	-0.90037	-4	-1.62623	-3	-1.14997	1	0.33292
S20	-2	-0.89384	2	1.05677	-4	-2.12308	-2	-0.92211
S21	-2	-1.02442	4	2.16414	-4	-1.16827	-3	-1.2303
S22	2	0.91496	-1	-0.49009	-1	-0.37126	-4	-1.80989
S23	-1	-0.56295	-2	-1.00895	-1	-0.44154	0	-0.13816
S24	-3	-1.17447	-4	-1.8808	-2	-1.01607	-1	-0.38952
S25	0	0.01676	0	-0.11766	1	0.34042	0	-0.12323
S26	1	0.81772	1	0.37243	1	0.30042	3	1.62004
S27	4	2.22604	0	-0.09862	2	0.44649	2	0.96401
S28	3	1.30518	-3	-1.02819	0	-0.22664	3	1.14896
S29	4	1.61578	-2	-1.01828	1	0.35515	3	1.10706
S30	-4	-1.73508	1	0.58852	-2	-0.8167	2	0.97403
S31	1	0.58783	3	1.55638	3	0.99778	4	1.75307
S32	0	-0.17343	0	-0.00972	0	-0.30112	1	0.37972
S33	-1	-0.70062	0	0.02877	-2	-0.76881	1	0.65091
S34	-1	-0.55768	4	1.63576	0	-0.32546	1	0.44144

and implementation. The second advocates for market-driven solutions, where the industry takes the lead in addressing interoperability challenges. The third focuses on specific technical features that interoperability should have. Lastly, the fourth perspective reflects a more conservative approach, favoring public-sector-led efforts to regulate interoperability.

A key finding of this study is the strong emphasis on supply-side interventions, whether through standardization or industry-led technological solutions. Notably, the study highlights a divergence from the existing literature on plug-and-play solutions, as stakeholders did not unanimously perceive them as the ultimate vision for interoperability. While most stakeholders agreed that standardization is a crucial strategy, there were significant disagreements over who should lead these efforts. Perspectives 1 and 4, for instance, sharply differ on whether the public or private sector should take the primary role in driving standardization initiatives.

On the methodological side, the Q methodology proves to be a powerful tool for exploring subjective perspectives. However, it has limitations, most notably the risk of researcher bias in concourse development and factor interpretation, as well as potential exclusion of non-technical perspectives due to participant selection criteria. Future research should build on these findings by including diverse participant groups and cross-country case studies to improve the reliability and depth of the findings. Additionally, real-world case studies on the successful implementation of interoperability in decentralized energy systems would provide valuable practical insights.

APPENDIX A
NOMENCLATURE

The terminologies, abbreviations and acronyms used in this study are summarized in Table 8.

APPENDIX B
Q SET

The statements used in this study and their thematic attributes are summarized in Table 9.

APPENDIX C
FACTOR RANKS AND Z-SCORES

The factors z-scores and corresponding ranks are presented in Table 10.

AUTHOR CONTRIBUTION

Conceptualization: AS, NM, JP; Data curation: AS, NM, JP; Formal analysis: AS; Investigation: AS, EAP, NM, JP; Methodology: AS; Supervision: EAP, NM, JP; Visualization: AS; Writing - original draft: AS; Writing - review & editing: AS, EAP, NM, JP.

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