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TOPICAL REVIEW

Interoperability in Microgrids to Improve Energy Access: A Systematic Review

AMALIA SURYANI[1], ILMAN SULAEMAN[1], OO ABDUL ROSYID[2], NIEK MOONEN[1], (Member, IEEE), AND JELENA POPOVIĆ[1], (Member, IEEE)
[1]Faculty of Electrical Engineering, Mathematics and Computer Science, University of Twente, 7522 NB Enschede, The Netherlands
[2]National Research and Innovation Agency (BRIN), Jakarta 10340, Indonesia

Corresponding author: Amalia Suryani (amalia.suryani@utwente.nl)

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ABSTRACT This paper presents a systematic review of microgrid interoperability focusing on energy access. Drawing upon 59 studies and reports, it delves into interoperability issues and technologies across various microgrid applications. This study aims to provide a synthesized overview of the current discourse on microgrid interoperability, particularly contextualized within the realm of energy access. This objective is accomplished through a process that involves clarifying terminologies, exploring potential interoperability issues in microgrids, identifying the technologies for interoperability, and examining promising pathways to achieve interoperability. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method was used in this study. Through data extraction and content analysis, the review found that studies on interoperability in the energy field primarily focus on the smart grid topic, where information and communication technologies are regarded as key elements to facilitate interoperability. There is less emphasis on physical or electrical interoperability, with the literature primarily focusing on interoperability in the communication domain. Furthermore, interoperability in the energy access context is uncommon, as indicated by a lack of literature in remote, rural, or community settings. Adopting common industry standards is one of the strategies for ensuring interoperability, enabling microgrid systems to function effectively and reliably. This paper contributes to describing research insights, identifying gaps in knowledge, and proposing future research directions regarding microgrid interoperability.

INDEX TERMS Energy access, interoperability, microgrid, PRISMA, standards, systematic review.

I. INTRODUCTION

The future of energy provision follows a vision of decarbonization, digitalization, and decentralization. This trend has made microgrids powered by renewable energy a prominent alternative to traditional electricity generation, as they generate clean energy, are supported by digital technologies, and can be located closer to customers [1]. Microgrids have become a promising solution to serve approximately 490 million people with electricity by 2030 as capital costs decline, new technologies emerge, and the enabling environment is conducive. Until 2021, around 21,500 microgrids had been installed worldwide and half of these microgrids are powered by solar technology [2]. There are, however, significant challenges hindering the adoption of microgrids as a solution for energy access. These challenges include sustainability issues, policy priorities, service quality, business models, and financing [3], [4], [5]. This study focuses on the technical sustainability of microgrids, particularly in the context of universal energy access. In this study, microgrids, also known as mini-grids, are defined as "electric power generation and distribution systems that supply electricity to local communities, covering domestic, commercial, and industrial demand. They can have varied sizes and can be fully isolated from the main grid or connected to it" [2].

A. MICROGRID RESEARCH

Microgrids can be categorized based on size, control strategies, power supply, energy sources, locations, and

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applications [6]. Microgrids in the energy access context commonly fall into the small-scale size with a decentralized control strategy, powered by either fossil fuel or renewable resources, located in remote rural areas, and used for residential purposes at the community level. They are often intended to operate in an islanded mode requiring an energy storage system.

Historically, microgrids have evolved from being simple and isolated (first generation) to hybrid systems combining conventional sources like diesel generators with renewable energy sources (second generation), and further to more multi-microgrid clusters, necessitating interconnected microgrids [7]. As the third generation of microgrid technology emerges, characterized by more advanced renewable integration and readiness for grid connection, modular and hybrid systems are anticipated to rise [2].

Microgrids are expected to play a significant role in the decentralized power system of the future [2], [8]. Research in this domain encompasses diverse disciplines, including engineering, economics, environmental studies, and social sciences, converging on the common goals of sustainable and resilient energy systems.

A recent review paper on microgrids [6] elaborates on four research areas in the technical domain. The first topic is operation and management, which includes design, energy management, operating modes, system security, power quality, control system, load balancing, and system stability. The second area of focus in microgrid research is component and compatibility, which includes equipment specifications, feeder design, telecommunication infrastructures, and communication protocols. The third area is the integration of distributed energy resources into the main grid. The fourth area is the protection system, which covers topics like short-circuit current, earthing, and protection coordination.

Uddin et al. [6] identified critical areas for future microgrid research. These research areas include microgrid system redesign with plug-and-play functionality, seamless transition from grid-connected to islanded operation, protection strategy in all modes and transitions, control techniques, generation-load stability, diverse features of the energy storage system, coordination among multiple microgrids, communication channel, policy, and standards.

B. STUDY MOTIVATION

Interoperability is a critical aspect of microgrid operation. Along with the energy transition and sustainable development agenda, more microgrid installations are anticipated in the Global South, complementing and competing with other technologies, such as solar lanterns, solar home systems, and grid extension. The coexistence of diverse technologies providing access to electricity poses challenges related to interoperability. These technologies, although designed to fulfill a common purpose, differ in functionalities, design, components, and capacity. They are rapidly advancing, driven among others by the declining costs of production and technological innovations such as efficient materials and digital technologies [2].

Bottom-up solutions, such as interconnected solar home systems, known as mesh grids or swarm electrification, require seamless integration of the household's systems. For example, a startup in the micro-energy transition model in Bangladesh has connected six million households [9], adopting a bottom-up approach and receiving assistance from specific manufacturers who may not use open standards. This may pose a risk of the technology being dependent on certain providers, which can hinder microgrid maintenance and replication [10]. When a component needs to be replaced due to breakage, obsolescence, or reaching its end-of-life, the operators and users in remote places face difficulty obtaining a replacement.

In different situations, the prospect of grid arrival can be quite high in villages with a microgrid system already in place. It is not unusual for the utility company to expand its grid as a village's electricity demand grows. This prompts the question of whether the existing microgrid can be interconnected to the grid, especially given that the future grid is expected to be more interconnected with numerous microgrids that can be powered by a variety of energy sources [11], [12].

The lack of integration capabilities among technologies could lead to competition or the abandonment of existing solutions when newer technologies with similar or superior functionalities emerge. Thus, interoperability becomes crucial for facilitating seamless integration. Whether these solutions coexist simultaneously, such as solar home systems alongside a main grid, or coexist shortly after the arrival of the grid in areas served by microgrids, interoperability remains a pressing issue. Additionally, even within the same solution, ensuring interoperability among sub-systems and components is necessary for effective operations.

Those scenarios lay out the rationale for addressing interoperability to improve microgrid implementation. Furthermore, these solutions differ technologically and in terms of stakeholders involved and business models.

Technological advancements, market dynamics, and energy policies shape the future of microgrid development [6], [13]. Focusing on technology in this study is essential because it directly affects the practical implementation and operation of microgrid systems. Technology is fundamental to address the technical challenges of interoperability. By identifying technical gaps, technology-focused research can help drive innovation in this field.

Despite its significance, interoperability in the context of energy access has received little attention. A review can play a crucial role in consolidating current knowledge, identifying existing gaps, and delineating future research directions [14]. Therefore, this review aims to provide a synthesized overview of the ongoing discourse about microgrid interoperability, specifically focusing on its relevance to energy access. The main question of this study is: How can interoperability in

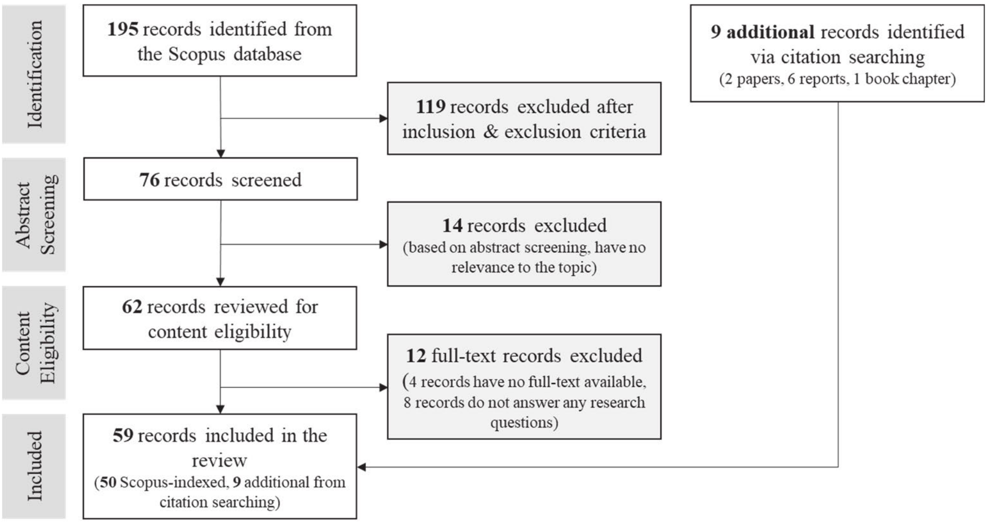

FIGURE 1. Document selection process.

microgrids be achieved to improve energy access? The main contributions of this work are:

- Characterization of scientific publications in microgrid interoperability using co-word analysis.
- Analysis of the issues related to interoperability in microgrid applications.
- Identification of technologies used and proposed to enhance microgrid interoperability.
- Identification of strategies to achieve interoperability in microgrids.

II. METHODOLOGY

This study is based on a systematic literature review (SLR) conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [15]. The SLR builds on an abstract published earlier in 2023 that identified the technologies for microgrid interoperability in energy access [16] and expands on it. Elaborating on the main question, this paper will address the following research questions:

- RQ1: What are the common interoperability issues in microgrids?
- RQ2: Which technologies are important for microgrid interoperability?
- RQ3: What strategies can be used to achieve interoperability in microgrids?

A. SEARCH STRATEGY

The authors developed a search strategy to compile a set of publications relevant to the research questions. In the first stage, a search for the term ''interoperability'' was performed to obtain an initial idea of the general research themes. Subsequently, the following terms and their spelling variations were included: ''microgrid,'' ''mini-grid,'' ''off-grid,'' ''distributed energy resource,'' ''compatibility,'' ''integration,'' ''energy access,'' ''rural electrification,'' ''rural,'' ''remote,'' and 'community.'' An advanced search function was used, and the search terms should appear in the title, abstract, and keywords. The terms were connected using the Boolean function operator ''AND,'' while the alternative synonyms were linked using the Boolean function operator ''OR.'' The asterisk symbol (*) was also used as a wildcard character to allow for proximity searches. Scopus database was chosen as the primary database because it offers broad coverage of disciplines [17], including technical publications published by IEEE. The search terms were refined through trial searches, with terms that did not generate additional records being excluded. Two terms were considered meaningful; ''interoperab*'' and ''m*grid.'' The final search of scholarly literature for this SLR was performed on February 19, 2024, which resulted in 195 documents.

B. ELIGIBILITY CRITERIA

To further select the relevant articles, a set of eligibility criteria was formulated, which cover the language, subject area, and document type. The inclusion and exclusion criteria are presented in **Table 1**, Additionally, the term ''interoperability'' must be present in the document as it is the central subject of this review.

TABLE 1. Eligibility criteria.

Element	Inclusion Criteria	Exclusion Criteria
Language	Written in English	Non-English documents
Subject Area	Limited to engineering and energy	Other areas than engineering and energy
Document Type	Journal articles, conference papers	Conference proceedings, books

C. REVIEW PROCESS

After applying the restrictions according to the criteria outlined in **Table 1**, the search returned 76 documents for review.

Two reviewers (AS and IS) screened all titles and abstracts and selected the relevant documents based on their relevance to the research questions. If the information in the title and abstract was insufficient to determine its inclusion, a brief screening of the full text was performed. Of the 76 abstracts screened, 14 documents were excluded as they were irrelevant, and four documents were removed as the full text could not be retrieved. Next, one reviewer conducted a full-text review and data extraction. After a full-text review, eight documents were excluded because they did not contribute to answering any research questions. There were 50 documents from the Scopus database, published in various journals and as conference papers, which were further processed for data extraction. In addition, nine documents from citation searching were included in the review. The selected documents were compiled using Mendeley Reference Manager. **Figure 1** depicts the process of obtaining 59 documents for this review. A complete list of these documents can be found in Appendix.

D. DATA EXTRACTION AND ANALYSIS

After retrieving the full-text documents, one reviewer extracted the data using a pre-specified sheet. To address any concerns regarding the preliminary results, all co-authors discussed the review process regularly. The process of abstract screening, full-text review, and data extraction was aided by the web-based software Covidence.org, allowing the review steps to be completed in one platform in collaboration among reviewers. The bibliographic details were recorded in an Excel worksheet. Lastly, to comprehensively synthesize the findings, all data was compiled into a single Excel workbook.

This review includes a bibliometric analysis in the form of keyword co-occurrence analysis (KCA) to identify the main thematic research areas within the interoperability literature. VOSviewer software version 1.6.18 [18] was used in those analyses. This review focused on qualitative data items, which were coded, analyzed, and summarized to answer the three research questions.

III. RESULTS

A. BIBLIOMETRIC ANALYSIS

Before delving into the topic of microgrid interoperability discussed in the 59 reviewed documents, we investigated studies on "interoperability" dating back to the first study in 1959. As shown in **Figure 2**, the topic began to proliferate around two decades ago and peaked in 2009 and 2022. It encompasses a wide range of disciplines, from computer science to dentistry, as depicted in **Figure 3**, indicating different applications of the interoperability concept. The energy subject area contains 2,236 documents, the first of which was from 1988.

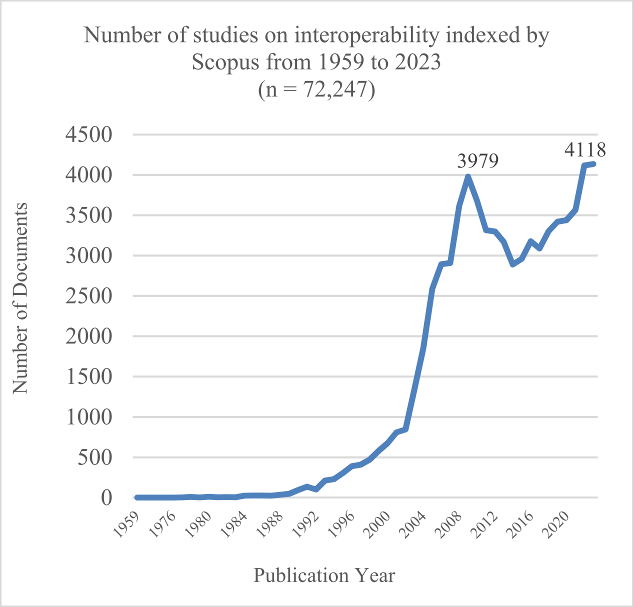

FIGURE 2. Number of documents on interoperability indexed by Scopus from 1959 to 2023.

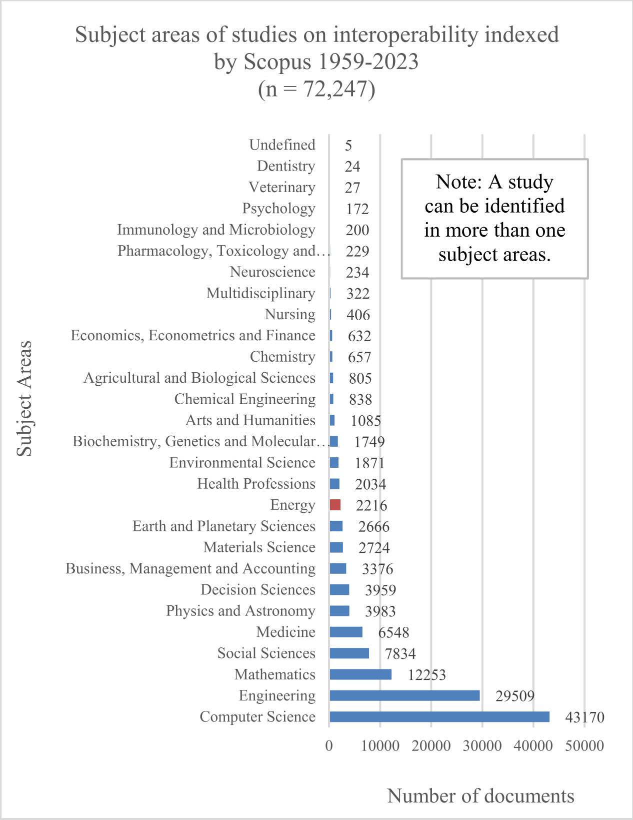

FIGURE 3. Subject areas of documents on interoperability indexed by Scopus from 1959 to 2023.

Two KCAs were performed for two sets of bibliographic data. **Figure 4** illustrates the keyword co-occurrence network of 2,236 Scopus-indexed documents on interoperability in the energy field. It only displays keywords with at least 50 occurrences. **Figure 5** illustrates the network of 76 Scopus-indexed documents that have undergone abstract screening in this study. This map only displays keywords with at least five occurrences.

A co-occurrence means two keywords appear together in a document. The different line colors represent different clusters of the study topics. These clusters indicate closely related themes. In a keyword co-occurrence network, the nodes represent keywords and the links between them indicate how frequently they appear together in the same documents. The node size represents the link strength to "interoperability"- the bigger nodes imply the stronger link. The total link strength indicates the number of documents in which they co-occur.

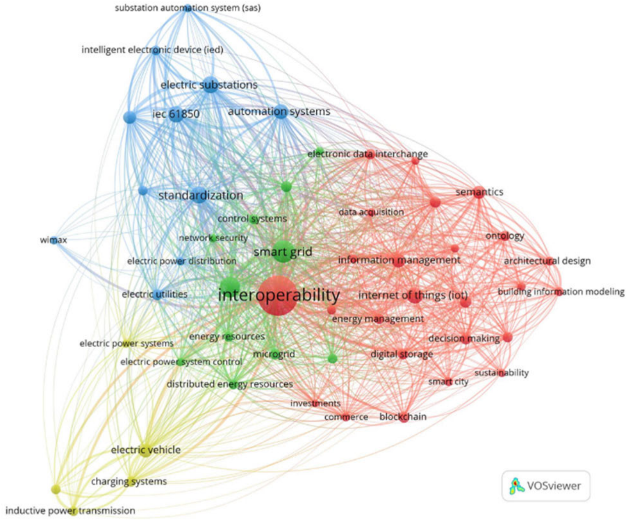

FIGURE 4. Keyword co-occurrence network of 2,236 documents on interoperability in the energy area.

Figure 4 reveals that the strongest link to "interoperability" was found in the "smart grid," i.e., in 383 publications out of 2,236 documents. Meanwhile, the keyword "microgrid" appears concurrently with "interoperability" less frequently, i.e., in 81 publications. The keywords "energy access" and "rural electrification" were not found in any documents. Despite the extensive body of research on interoperability, the intersection of this concept with rural microgrids is non-existent.

KCA on the 76 Scopus-indexed documents, as shown in **Figure 5**, reveals three clusters of themes, each containing a list of keywords. Each cluster and its keywords are presented in **Table 2**. The term "interoperability," located in the center, is connected to all clusters as it was the focal point of the study. Cluster 1, colored red, is home to documents that discuss interoperability in microgrid and smart grid applications. Cluster 2, colored green, is concentrated on electric power transmission and energy management systems. In this cluster, standardization and IEC 61850 emerged as relevant keywords, indicating the significance of communication standards in energy and information management. Cluster 3, colored blue, discusses control and communication.

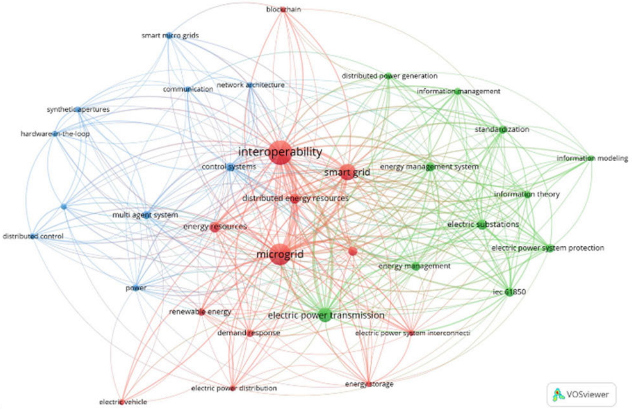

FIGURE 5. Keyword co-occurrence network of 76 documents that met the inclusion and exclusion criteria.

TABLE 2. Network clusters of the 76 abstract screened.

Cluster 1	Cluster 2	Cluster 3
interoperability	electric power transmission	control systems
microgrid	electric substations	multi-agent system
smart grid	IEC 61850	power
distributed energy resources	energy management system	distributed parameter control systems
energy resources	electric power system protection	distributed control
renewable energy resources	energy management	hardware-in-the-loop
electric power system interconnection	standardization	synthetic apertures
energy storage	information theory	network architecture
demand response	information management	communication
renewable energy	information modeling	smart microgrids
electric power distribution		
blockchain		
electric vehicle		

B. TERMINOLOGIES

Multiple definitions exist to explain the concept of interoperability and what it entails. Within this review, seven definitions were identified, as shown in **Table 3**. Among these, the first six share certain commonalities, placing a strong emphasis on information exchange and effective operation within a shared environment (for instance, on the same energy supply). However, the last definition adopts a wider perspective, encompassing a spectrum that ranges from physical or electrical compatibility to the communication domain that involves information exchange and utilization to even more complex relationships like component interchangeability.

The terms "compatibility" and "interchangeability" were introduced in the fourth source [22], with the latter referring to the characteristics of two or more entities that can be used or substituted for one another without a significant difference in function. To illustrate the distinction between these terms, **Figure 6** provides a visual interpretation of the three terms.

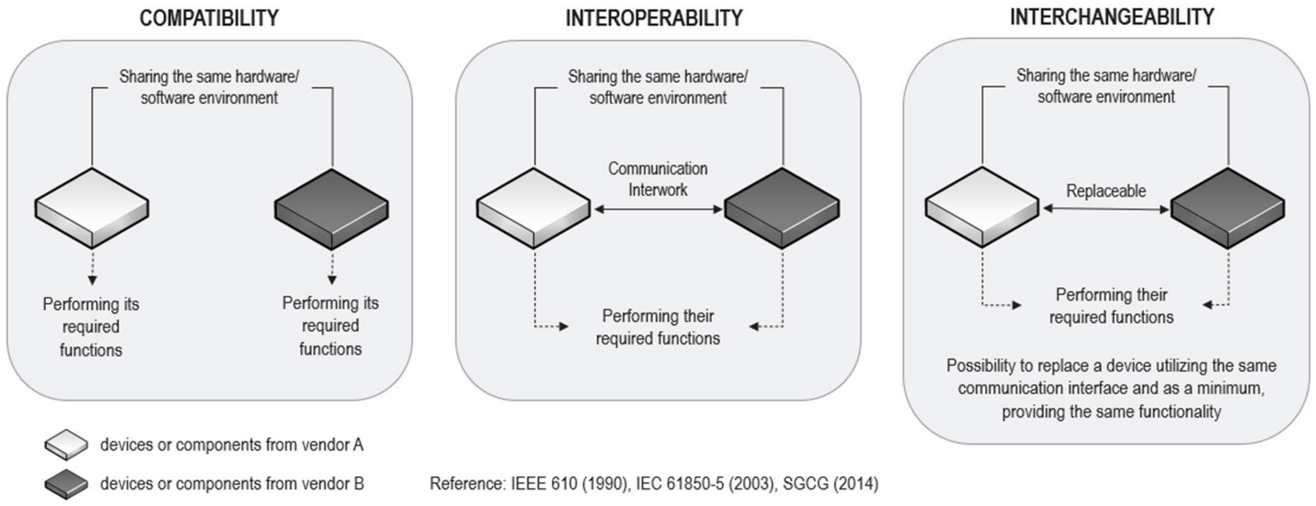

FIGURE 6. Visualization of compatibility, interoperability, and interchangeability [13], [14], [16].

TABLE 3. Definitions of interoperability.

Ref	Definition
[19]	"The ability of two or more systems or components to exchange information and to use the information that has been exchanged."
[20]	"The ability of two or more intelligent electronic devices from the same vendor, or different vendors, to exchange information and use that information for correct co-operation."
[21]	"The capability of two or more networks, systems, devices, applications, or components to externally exchange and readily use information securely and effectively."
[22]	"The ability of two or more networks, systems, devices, applications, or components to interwork, to exchange and use the information to perform required functions."
[23]	"The ability of two or more intelligent electronic devices from different vendors to exchange information and use that information for correct execution of specified functions."
[24]	"Interoperability allows the network to seamlessly and autonomously integrate all components of power, distribution, management, and communication while minimizing human intervention."
[11]	"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."

C. INTEROPERABILITY ISSUES IN MICROGRIDS

The goal of interoperability is for a system to be able to configure and integrate a component into the system by simply plugging in, i.e., plug-and-play [11], [24], [25], [26]. According to **Table 3**, the definition of interoperability covers a wide spectrum from component/device up to system levels. Consequently, microgrid interoperability can apply to three levels: interoperability between components and devices within a microgrid, interoperability between a microgrid with other decentralized energy resources (DERs), and interoperability between a microgrid and the main grid in case of grid interconnection. The latter is often discussed in smart grid literature. **Table 4** provides a list of issues related to interoperability which were discussed in the reviewed literature.

Several interoperability issues were mostly discussed in the reviewed literature and are shown in **Figure 7** Aside from the issues depicted in the chart, other issues like reliability, monitoring, energy management, and physical security were also addressed. The following subsections will go over six topics: communication, control, cybersecurity, interconnection, compatibility, and electrical protection.

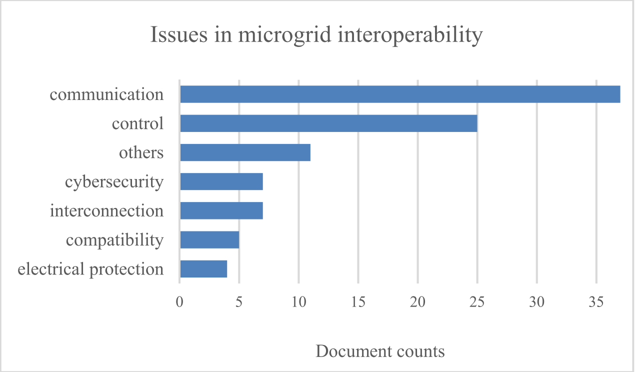

FIGURE 7. Most discussed issues in the literature.

1) COMMUNICATION

Effective communication stands out as the paramount element of interoperability, as implied by interoperability definitions outlined in **Table 3**. Communication issues were discussed in more than half of the reviewed literature, within the themes of energy management systems, control, monitoring, and integration of DERs. Communication distinguishes interoperability from compatibility; to be interoperable, microgrid components and systems must be able

TABLE 4. Issues related to microgrid interoperability.

Issues	Specific Applications Discussed in the Literature	Ref
Communication	Energy management system, energy storage system, control system, monitoring system, SCADA, inverter, smart meter, intelligent electronic devices (IEDs), PV forecasting, load prediction	[10], [11], [12], [22], [26], [27], [28], [29], [30], [31], [32], [33], [34], [35], [36], [37], [38], [39], [40], [41], [42], [43], [44], [45], [46], [47], [48], [49], [50], [51], [52], [53], [54], [55], [56], [57], [58]
Control	Control system, SCADA, monitoring system, energy management system, energy scheduling,	[12], [24], [25], [30], [35], [36], [41], [44], [49], [50], [54], [59], [60], [61], [62], [63], [64], [65], [66], [67], [68], [69], [70], [71], [72]
Cybersecurity	Control system, monitoring system	[43], [49], [50], [51], [52], [64], [67]
Interconnection	Control system, monitoring system, smart meter	[28], [32], [43], [44], [54], [73], [74]
Electrical protection	Control system	[23], [50], [72], [73]
Compatibility	Control system	[11], [16], [22], [31], [64]

to exchange information and use it without impeding their functionality [11], [26], [52].

Communication challenges arise in microgrids due to the use of different communication protocols among components, hindering seamless interaction and information sharing. Devices from different vendors may have proprietary communication procedures that limit the ability to interconnect different components [10]. The presence of varied and incompatible communication protocols introduces the potential risk of undermining the responsiveness of systems that necessitate real-time communication among different resources [35], [52]. Inverters, for instance, must demonstrate the capability to communicate effectively with other devices and use the information to perform their functional tasks [52]. Addressing these issues is crucial for enhancing the overall efficiency and reliability of microgrid operations.

Various communication technologies and standards may coexist within different segments of a microgrid system. Consequently, it becomes imperative to establish universal communication protocols in the microgrid field. An example of such standardization is found in the Open Field Message Bus (OpenFMB), which serves as an open standard dedicated to communication and interoperability. OpenFMB defines a reference architecture that facilitates peer-to-peer communication among devices, enabling the exchange of data and information for distributed control, particularly in microgrid applications [12], [59]. The adoption of such universal communication rules promotes cohesion in the diverse technological landscape of microgrids.

2) CONTROL

Microgrid control structure can be organized into a three-level hierarchy: primary, secondary, and tertiary [12], [41], [71], [75]. Primary control is implemented in local DER controllers, responsible for maintaining reference voltage and frequency to ensure a stable microgrid operation [75]. These controllers are used during islanded mode operation, focusing on DER regulation. In instances where fluctuations in load and generation cause voltage and frequency deviations, secondary-level controllers come into play to make necessary adjustments. When connecting a microgrid to an external grid, the secondary-level controllers handle voltage and frequency synchronization [75]. At this level, two control approaches can be implemented: centralized and decentralized. Tertiary control can be considered as the interaction of multiple microgrids with a main grid [71]. At this level, optimization, and decision-making functions are applied, providing optimal set-points to lower-level controllers, and thereby achieving intelligent and more efficient overall system operation [12], [75]. Ensuring the reliability, efficiency, error-free operation, and interoperability of a microgrid system requires the implementation of an appropriate control scheme [25], [75].

The control system plays a crucial role in overseeing the microgrid's operation and harmonizing the various components to achieve optimal performance. A well-designed control layer becomes imperative for the seamless operation of a microgrid, facilitating its collaboration with other systems, managing supply and demand, and regulating the transition between grid-connected and islanding mode operations [75]. These tasks are particularly demanding for microgrids powered by renewable energy sources, given their intermittent generation and highly distributed characteristics. Therefore, reliable communication links are essential for the control system to function effectively, enabling multiple controllers to communicate control commands and information [41], [71].

3) CYBERSECURITY

Communication challenges are often linked to issues in cybersecurity. As microgrid systems continue to evolve and expand their interconnectivity, there is a greater risk of security breaches. The extent to which a microgrid system is connected to the Internet plays a critical role in intensifying these security risks. The more integrated a microgrid with external networks, the more vulnerable its security becomes. Cyberattacks can involve various malicious activities, such as unauthorized access to unencrypted data stored on the cloud, breaching an organization's internal management systems, and disrupting microgrid operations, for example, by generating false alarms [52], [67]. Therefore, to safeguard microgrid systems against these threats, it is imperative to integrate cybersecurity considerations into the system design at the earliest stages [50]. In 2018, the interconnection standard IEEE 1547 was revised to require DER to include security measures including privacy protection, encryption, authentication algorithms, intrusion detection, and key management requirements [51], [52]. Furthermore, data privacy is equally important particularly when it comes to maintaining customer trust [49].

4) INTERCONNECTION

The literature explores interconnection issues across various domains, encompassing device-to-device [32], [43], [44], network-to-network, and system-to-system interconnections [28], [43], [54], [73]. Interconnection among devices, such as sensors and controllers, and power electric systems, such as DERs with an external grid, requires interoperable hardware (physical components) and software architectures.

A conventional electricity grid typically is composed of three main elements: generation, transmission, and distribution, to meet the load or demand. Similarly, a microgrid also consists of these three elements: generation-distribution-load. But when a microgrid is interconnected with an external grid, it assumes a flexible role, functioning either as a generator or as a consumer, depending on the balance between its internal supply and demand. Grid interconnection makes it possible to import power from another source to make up for power deficits experienced by microgrids, effectively turning the microgrid into a consumer. On the other hand, the microgrid can export its excess power to the grid, acting as a generator.

More system interconnection is expected in anticipation of growing demand and the future transition from basic and isolated microgrids to multi-microgrid clusters. In addition to ensuring microgrid energy security, grid interconnection increases grid efficiency by bringing more generations closer to the load. Microgrids can be considered as multiple individual entities that can be controlled to support the upstream grid [28]. This can only be realized if the microgrids are interoperable with the grid, which can be challenging given that each microgrid is designed differently depending on several factors such as demand, available resources, and technology used. Protection, power quality limitations, reconnection and synchronization, voltage regulation, reactive capacity, and frequency regulation are important factors to consider for microgrid interconnection [73]. Energy management tasks such as generation-load balance and advanced controllers are also critical. Recently, Liu et al. [76] proposed a dual-mode energy management system for distributed microgrids that can operate adaptively in islanded mode, grid-connected mode, and switching modes.

5) COMPATIBILITY

Compatibility is about ensuring that different components can coexist, interact, and function together in the same environment without causing problems for each other [19]. This concept encompasses various elements of a power system, ranging from electrical and physical aspects [11] to data and communication [31]. While the significance of communication compatibility is detailed in Section III-C.1, it is crucial to highlight that electrical and physical compatibility are equally vital for fostering interoperability. In electrical compatibility, the compatible power rating is a prerequisite, necessitating standardization to define the capabilities and operation limits of each equipment. This standardization helps prevent overloading other equipment within microgrids. The complexity intensifies in multi-microgrid cluster and grid interconnection scenarios due to the wide variation in equipment power ratings and operational limits.

As electrical compatibility is examined more closely at the component and device levels, electromagnetic compatibility (EMC) emerges as a crucial consideration. EMC can be defined as ‘‘a characteristic of electrical and electronic equipment that permits it to operate as intended in the presence of other electrical and electronic equipment, and not to adversely interfere with that other equipment’’ [77]. EMC is essential in the microgrid context, where renewable energy sources and power electronic devices are used. The use of power electronic devices, such as converters, introduces electromagnetic interference, potentially causing malfunctions in other devices and systems within the microgrid. Unfortunately, this has not been discussed, especially in energy access.

Regarding physical compatibility, various definitions have been used to characterize its scope, encompassing considerations such as data transfer, devices, infrastructure, components, hardware, and firmware that are linked to the microgrid [10], [11]. Notably, there seems to be a noticeable gap in discussions concerning the significance of physical compatibility in terms of mechanical aspects, such as universally compatible sockets or all-in-one plugs. While it is important to ensure that one device can be physically connected to another device to foster interoperability, this is often not the case, especially within the realm of energy access technologies.

6) ELECTRICAL PROTECTION

A robust protection scheme should have the capability to detect and isolate system failures, prevent equipment damage, and minimize the risk of personnel injury. This, in turn, ensures the microgrid safeguards against various faults, guaranteeing secure and reliable operation, which protects the microgrid against all kinds of faults and provides assured safe and secure operation. However, a major relevant challenge to microgrid protection lies in developing an effective protection strategy that caters to both grid-connected and islanded modes of operation [23], [50], [73]. The protection system must accurately isolate faults, providing defense mechanisms to shield the grid from microgrid-induced faults or vice versa. This dual functionality ensures minimal disruptions in either system, enhancing overall operational stability.

A microgrid's protection system may have distinct trip characteristics, potentially causing conflicts and operational delays. Trip characteristics denote how the protection system behaves upon detecting a fault. For instance, differing response times among protection systems can lead to undesirable conditions, particularly if a trip occurs at the upstream grid and the protection system close to the fault point fails to trip due (for example, due to a higher acceptable limit). Incompatibility between the protection systems in the microgrid can compromise efficiency and performance and pose safety risks. Defining the protection scheme should also consider the microgrid's capability to operate in islanded conditions, fault identification capability, distributed generation penetration, short circuit levels, and the availability of storage and/or spinning reserve in the microgrids [73], [78]. Ensuring seamless microgrid operation requires not only compatibility but also a harmonious interaction among the protection systems.

D. TECHNOLOGIES FOR INTEROPERABILITY

A three-dimensional framework for the design and implementation of microgrid systems was proposed in [10], which consists of five interoperable layers i.e., physical, information and communication technologies (ICT), control, market and business, and regulatory layers, as shown in **Figure 8**. The physical layer involves all physical components including power electronics equipment and loads. It is the first point of data submission acquired from meters and energy management systems installed in different points. The ICT layer addresses data relays through communication protocols. This layer facilitates information exchange, which makes it essential for interoperability. The control layer has the function to collect data from the other layers, make predictions based on data, and make decisions in microgrid operation. The market and business layer deals with business models and market operations, such as managing Peer-to-Peer (P2P) trading and allocating each customer's energy quota. Legal frameworks and regulations, such as standards for microgrid design, operation, and interoperability, are included in the regulation layer. Microgrid adoption depends on this layer, especially in terms of interconnection to the main grid. In general, the framework underlines easy integration and communication with smart grid networks, as well as user participation in the energy markets.

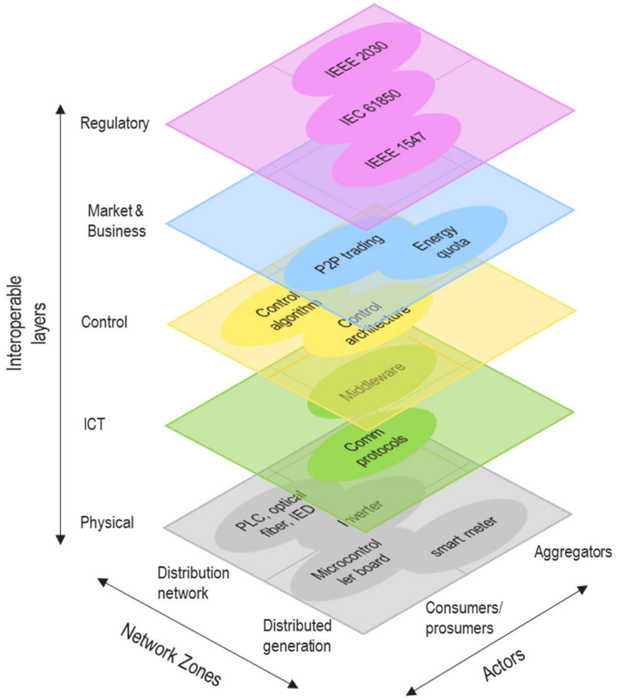

FIGURE 8. **Interoperability layers and some technologies to help achieve interoperability in microgrids. Adapted from [10] and [16].**

Technologies for interoperability can be physical, conceptual, and prescriptive, for example, in the form of technical standards. Most of the reviewed documents suggest technological solutions within the ICT layer, followed by the control layer. Whereas technologies for the physical layer as well as the market and business layer were only touched on in a few documents.

Furthermore, since interoperability is often defined as the ability to exchange information in a timely and actionable manner, the authors in [10] suggest that the ICT and control layers are particularly important for achieving interoperability and scaling up microgrids. The ICT layer enables the information exchange between the different components in a microgrid and between microgrids. Notable among communication-related technologies are OPC, DDS, GOOSE, CIM, DNP3, and OpenFMB, which are frequently discussed and proposed in the literature, as listed in **Table 5**.

Microgrids rely on ICT and control layers to integrate diverse energy resources, manage distributed energy storage, and provide effective control mechanisms. The ICT layer facilitates communication between various components such as inverters, storage devices, load controllers, and monitoring sensors. This may include real-time data exchange protocols that allow control commands to be issued in real-time [80]. Interoperability within the control layers ensures that control strategies and algorithms implemented across different components are compatible and can interact seamlessly. Examples of control algorithms that require interoperability include algorithms for load shedding and voltage regulation [60], [80].

In power systems, interoperability within the ICT layer is critical for grid monitoring, control, and optimization. It enables efficient energy management, grid stability, and integration of renewable energy sources. This may include communication protocols for supervisory control and data acquisition (SCADA) systems [25], [43], [44], [60], [66] and advanced metering infrastructure [10], [43].

Seven out of 59 documents reviewed in this paper discussed cybersecurity concerns related to interoperability. Increasing interoperability leads to increasing interconnected systems which involves communication and data sharing of diverse components such as inverters and control systems.

TABLE 5. **Most discussed communication technologies for microgrid interoperability.**

Technology	Description	Ref
OPC	Object Linking and Embedding for Process Control (OPC) is a technology for standardized data exchange that deals with heterogeneity and interoperability. Its primary goal is to enable interoperability and seamless data exchange between diverse hardware and software components in a system, especially related to automation in an industrial environment.	[36], [41], [43], [44], [53], [58], [60], [67], [69], [71]
DDS	Data Distribution Services (DDS) is an open-access communication protocol for real-time communication and information exchange, enabling integration of devices from various vendors	[10], [32], [33], [43], [45]
GOOSE	Generic Object-Oriented Sub-Station Event (GOOSE) is a standardized messaging mechanism as part of IEC 61850, that can communicate critical messages in real-time	[34], [35], [48], [67], [79]
CIM	Common Information Model (CIM) is a standardized information model presented in IEC 61970, that is expressed in a unified modeling language (UML) making it easier to exchange information between different systems and devices.	[36], [42], [60], [80]
DNP3	Distributed Network Protocol 3 (DNP3) is an open communication protocol widely used in electric power systems for communication between various components. It is also suggested in IEEE 1547 to support the interconnection and interoperability of DERs.	[55], [61], [67], [79]
OpenFMB	Open Field Message Bus (OpenFMB) is an open communication standard that enables secure, reliable, and scalable communications and information exchange among devices on an electric grid. OpenFMB adapters serve as translators across various protocols like DDS, GOOSE, and DNP3.	[12], [39], [59], [61]

This interconnectedness increases the potential cyber-attacks if the cybersecurity measures are weak. Cybersecurity concerns are closely related to communications [50], [51], [52], control [43], [50], [64], [67], and real-time monitoring [43], [64], where the solution is found in the standardized cyber security practices. Obert et al. [51] suggested Trusted Computing (TC) architectures available for smartphones can be leveraged for trust management in smart inverters. Gopstein et al. [49] suggested that a standardized risk framework should include interoperability and cybersecurity standards, to address the expanding communications and digital controls in energy systems.

A recent review paper on microgrid protection [78] discussed various mitigation strategies for different protection issues. The authors proposed protection schemes based on the microgrid's topology, size, fault type, configuration, and operating modes. Adaptive, differential, directional, under/over voltage, and digital protection schemes are among the schemes suitable for faults during islanded and grid-connected modes [78]. Most protection schemes require a communication link, which highlights the importance of interoperability. A digital protection scheme, for example, may include equipment from multiple vendors, such as a Phasor Measurement Unit (PMU), IEDs, and circuit breakers, requiring interoperability [72] governed by technical standards.

E. STRATEGIES TO ACHIEVE INTEROPERABILITY

Interoperability in microgrids can be achieved through different strategies: the use of standards [10], [26], [54], setting and compliance to detailed system specifications [26], and system testing that includes conformance and interoperability testing [26]. Technical standards can guide the industry to meet certain levels of product and system quality. Open standards can facilitate interoperability [26], even though conformance to standards does not guarantee interoperability [23], [24]. System specifications can facilitate knowledge transfer so that all actors have the same understanding of a system configuration. Meanwhile, system testing can help identify compatibility issues and ensure that a system adheres to technical standards and specifications.

Different technologies require effective cooperation among units and systems from different manufacturers. When a microgrid uses non-proprietary solutions, there is a risk of different standards from different domains being adopted, such as standards coming from the power system domain or communication domain [10].

Achieving interoperability is one of the reasons why standards are developed. Microgrid interoperability can be facilitated by information and communication technologies that allow two-way communication and effective information exchange among components, devices, and systems, which enables a feedback mechanism between the electricity producer and consumers. Interoperability standards have the potential to enhance decentralized control of DERs [49], although the development of certain standards may pose engineering challenges [41]. While general technical requirements and testing procedures for grid interconnection are outlined in standards like in IEEE 1547, operational limits can vary due to contextual factors such as the environment and local regulations [73]. Consequently, implementation of the standards and a consistent adaptation to the local requirements is required to prevent future interoperability issues. **Table 6** summarizes several standards discussed in the reviewed publications, that specifically address interoperability issues.

IV. DISCUSSION

A. INTEROPERABILITY IN THE ENERGY ACCESS CONTEXT

The reviewed literature on interoperability primarily covers AC systems, emphasizing microgrid capability to interconnect with the grid. Consequently, discussions revolving around microgrid interoperability often intersect with the realm of smart grid applications, in which the concept

TABLE 6. Standards discussed in the reviewed documents.

Standard Name	Topics Covered	Ref
IEC 61850 Series	• Communication networks and systems in substations. • Specifications for decentralized energy resources (DER) and control systems (IEC 61850-7-4).	[10], [12], [23], [24], [33], [34], [35], [36], [37], [38], [41], [43], [47], [48], [61], [66], [67], [69], [71], [72], [79], [80]
IEC 61968	• Information exchange methods in electric power systems (EPS). • Associated with the Common Information Model (CIM).	[41], [60], [80]
IEC 61970	Energy management system application program interface.	[10], [41], [60], [80]
IEEE 2030	• Guide for smart grid interoperability of energy technology and information technology operation with the EPS, end-use applications, and loads. • Smart grid interoperability reference model (SGIRM) as a reference tool to provide stakeholders with a common understanding of interoperability criteria from the power system, communications, and information technology perspectives. • It offers the most comprehensive technical procedure to define the functions of a microgrid controller.	[10], [27], [42], [50], [52], [54], [55], [73]
IEEE 1547 Series	• Interconnection between distributed energy resources (DER) with EPS. • A guide for design, operation, and integration of distributed resource island systems with electric power systems. • Addresses guidelines for monitoring, information exchange, and control for DER interconnections (IEEE 1547.3). • Addresses integration of microgrids with the main grid, although it does not contain any techniques regarding interoperability, but it addresses the compatibility issues of ground among the DER, transformer, and EPS (IEEE 1547.4).	[10], [27], [28], [54], [55], [61], [71], [73]
IEEE 802 Series	• A collection of networking standards that cover the physical and data link layer specifications for technologies such as Ethernet and wireless. • The active standards include IEEE 802.3 (Ethernet), IEEE 802.11 (Wireless LAN and Mesh/Wi-Fi certification), IEEE 802.15 (Wireless PAN), and IEEE 802.16 (WiMAX, which stands for Worldwide Interoperability for Microwave Access).	[10], [32], [57]

of interoperability layers for the Smart Grid Interoperability Reference Model (SGIRM) originally emerged [21]. The analysis of keyword co-occurrences, as illustrated in **Figure 4**, supports this conclusion, highlighting the strong linkage between interoperability and the smart grid.

Discussions about microgrids can vary depending on the region and context. In the United States and Europe, microgrids are often viewed as a technology to enhance the main grid rather than being the primary source of electricity. On the other hand, in many Global South countries such as India, Indonesia, and Nigeria, a lot of microgrids operate in stand-alone mode, serving a limited number of households. This diversity suggests that microgrids are a broad and context-specific topic. As a result, the challenges related to interoperability vary across various contexts.

In the domain of DC microgrids, standardizing components like power electronic converters helps ensure different equipment from different vendors can work together seamlessly. The aim is to achieve plug-and-play functionality, enhancing the microgrid's overall interoperability. Within AC microgrids, the significance of interoperability amplifies when these microgrids are connected to a larger electrical grid, enabling bidirectional power flows. Notably, control strategies will vary between small, isolated microgrids and larger, multiple interconnected systems, requiring more complex interoperability measures. However, differences in interoperability issues among various microgrid configurations such as hybrid microgrids and microgrid clusters are not highlighted in the literature.

B. LACKING ATTENTION ON PHYSICAL/ELECTRICAL INTEROPERABILITY

One notable distinction among definitions in literature lies in the interpretation of interoperability. While the official terminologies published by IEEE and IEC consider interoperability as a communication issue, a practitioner organization in the energy access sector [11] extends the scope to encompass a broader spectrum of "interactions." This expanded view includes not only physical and electrical connections but also more intricate relationships involving the exchange of information between components. While the prevailing perspective in the literature underscores interoperability as the ability for system components from diverse domains to interact, it is crucial to highlight the significance of establishing connections and ensuring their compatibility, both electrically and physically. This broader focus is vital for fostering effective and sustainable communication.

Having devices that are electrically compatible with a wide range of appliances is desirable as it opens broader possibilities for interoperability. However, achieving physical compatibility, such as fitting into sockets and plugs seamlessly, poses challenges. This is primarily because these physical designs are typically tailored to meet the technical requirements of specific applications, such as factors like voltage and current ratings, safety features, adherence to local standards, and environmental conditions.

Despite the complexities, ensuring physical compatibility is crucial, particularly in the context of energy access where bottom-up approaches are employed to avoid the abandonment of technology. For example, certain energy access technologies deliver low-power electricity through low voltage, such as 5, 12, and/or 24 V DC supplies, and expansion often relies on proprietary devices, limiting the range of appliances that can be connected. The users should be able to choose, therefore, it becomes imperative for these technologies to be interoperable with other bottom-up technologies or larger systems, especially as the utilization of energy increases, and the potential for multi-microgrid clusters and/or grid connections grows.

As most current research has focused on the ICT and control layers, it is questionable whether the physical layer is therefore (albeit implicitly) assumed to be already interoperable, especially to accommodate fast technology developments. Therefore, a gap in the literature can be identified, although this might be a case of alternative terminology in the different layers of interoperability. As an example, the IEC 61000-4-30 (which defines the methods for measuring and interpreting results of power quality parameters in AC power supply systems with a declared fundamental frequency of 50 Hz or 60 Hz) and EN50160 (which specifies the main characteristics of the voltage at a network user's supply terminals in public low voltage, medium, and high voltage AC electricity networks under normal operating conditions) are attributed to the physical layer. According to the illustration **Figure 7**, they, they are under the compatibility category; however, by introducing a communication link to condition both supply and demand quality, one can achieve interoperability. Electromagnetic compatible systems are inherently overdesigned and electromagnetic interoperable systems allow for careful optimization to include the time domain fluctuations of power supply and demand balancing.

C. METHODOLOGICAL LIMITATIONS

There are limitations associated with using the PRISMA method for systematic literature reviews. We identify four aspects namely search strategy, subjectivity, risk of data extraction errors, and publication lag.

Despite a comprehensive search strategy, some relevant studies may be excluded from the review due to limitations in search terms and databases used. In this paper, an important selection criterion for publications is the explicit use of the terms "interoperability" and "microgrid," as well as their spelling alternatives, in the title, abstract, or keywords. We are aware that studies on microgrid interoperability that do not explicitly use these terms may be excluded. However, given these keywords' specificity, these terms were required for inclusion in this study.

The subjective nature of the researchers involved in the review made assessing the quality of the documents challenging. The risk of researcher bias was mitigated by using rigid selection criteria and having two researchers screen the abstracts.

The data extraction process was done manually by thoroughly reading each selected document. This approach has the advantage of providing a better understanding of the study's context while increasing the risk of errors. The researchers addressed this issue by using a data extraction sheet with predefined properties.

Publication lag is a common risk in systematic reviews. As these reviews take time to conduct, recent studies may emerge by the time they are completed and published. This can potentially affect the relevance and accuracy of the findings. It is therefore advisable for readers to be mindful of the document selection process, including the scanning period.

V. CONCLUSION AND FUTURE WORK

This systematic review aims at consolidating the discourse surrounding microgrid interoperability and its significance in improving energy access. The study sheds light on the subtle distinctions between interoperability, compatibility, and interchangeability, while also highlighting the physical and electrical requirements for a system to be interoperable. Interoperability was primarily viewed as a communication issue in the existing literature. However, a broader definition emerged in 2018 encompassing both the physical/electrical domain and communication domain, expanding our understanding of this critical concept.

Through a comprehensive synthesis of the selected literature, the study reveals that microgrid interoperability revolves around smart grid applications and grid integration scenarios in developed regions. Particularly noteworthy is the focus on information and communication technologies (ICTs) as prominent solutions for tackling interoperability issues. However, the literature provides limited insights into interoperability within the energy access context, indicating gaps in our comprehension and paving the way for future research directions. Moreover, interoperability is not only an issue of technology. It requires shared understanding among stakeholders and recognition of its needs. In our upcoming work, we will delve into stakeholder perspectives on interoperability, with a specific focus on the energy access domain. Stakeholders with diverse backgrounds and expertise will bring unique insights to such a complex issue as interoperability. They will help identify concerns and priorities and will help in the decision-making process for strategies to achieve interoperability. Furthermore, future research in microgrid interoperability could focus on investigating interoperability issues across various microgrid configurations, such as standalone microgrids, hybrid microgrids, grid-connected microgrids, and microgrid clusters comprising multiple interconnected microgrids.

APPENDIX

LIST OF REVIEWED DOCUMENTS

The reference numbers are in the order in which they appear on the paper.

Research Questions (RQs)

- RQ1: What are the common interoperability issues in microgrids?
- RQ2: Which technologies are important for microgrid interoperability?
- RQ3: What strategies can be used to achieve interoperability in microgrids?

TABLE 7. All Reviewed documents selected through database search and citation search.

ID	Title	Author	Year	Contribute to			Ref
				RQ1	RQ2	RQ3	
1	Distributed Service Choreography Framework for Interoperability Among Prosumers and Electric Power System	Kannisto P.; Gumrukcu E.; Ponci F.; Monti A.; Repo S.; Hastbacka D.	2023	x	x	-	[56]
2	Communication Latency Assessment for an Interoperability Interface Prototype Applied to Power Converters in Laboratory Microgrids	Paulo V.S.C.; De Oro Arenas L.; Alonso A.M.S.	2023	x	x	-	[57]
3	Design and Implementation of an OPC UA-Based Cloud System for the Management of Distributed Microgrid Networks	Lee C.; Im J.; Kwon H.-Y.; Lee Y.I.	2023	x	x	-	[58]
4	A Feasibility Study of Implementing IEEE 1547 and IEEE 2030 Standards for Microgrid in the Kingdom of Saudi Arabia	Alsafran A.S.	2023	x	-	x	[27]
5	Technologies for Interoperability in Microgrids for Energy Access	Suryani A., Sulaeman I., Popovic J., Moonen N., Leferink F.	2023	x	x	-	[16]
6	Microgrid Applications and Technical Challenges—The Brazilian Status of Connection Standards and Operational Procedures	Castro J.F.C., et al.	2023	x	-	x	[73]
7	Interoperability of single-controllable clusters: Aggregate response of low-voltage microgrids	Junior J.R.S., Conrado B.R.P., dos Santos Alonso A.M., Brandao D.I.	2023	x	x	x	[28]
8	Community-Based Microgrids: Literature Review and Pathways to Decarbonise the Local Electricity Network	Trivedi R., et al.	2022	x	x	x	[10]
9	Refined Network Topology for Improved Reliability and Enhanced Dijkstra Algorithm for Optimal Path Selection during Link Failures in Cluster Microgrids	Pradeep Reddy G., Kumar Y.V.P., Kalyan Chakravarthi M., Flah A.	2022	x	x	-	[29]
10	A Framework for Coordinated Self-Assembly of Networked Microgrids Using Consensus Algorithms	Schneider K.P., et al.	2022	-	x	x	[59]
11	Reducing Detrimental Communication Failure Impacts in Microgrids by Using Deep Learning Techniques	Arbab-Zavar B., Sharkh S.M., Palacios-Garcia E.J., Vasquez J.C., Guerrero J.M.	2022	x	x	-	[30]
12	Modular Microgrid Controller on OpenFMB Standard	Bailapudi M.P.K.	2022	-	x	x	[12]
13	Implementation of a coordinated voltage control algorithm for a microgrid via SCADA-as-a-service approach	Nguyen V.H., Tran Q.T., Buttin H., Guemri M.	2022	-	x	x	[60]
14	Communication Technologies for Interoperable Smart Microgrids in Urban Energy Community: A Broad Review of the State of the Art, Challenges, and Research Perspectives	Reddy G.P., Kumar Y.V.P., Chakravarthi M.K.	2022	x	x	-	[31]
15	A time-sensitive networking-enabled synchronized three-phase and phasor measurement-based monitoring system for microgrids	Agarwal T., Niknejad P., Rahmani F., Barzegaran M., Vanfretti L.	2021	x	x	x	[32]
16	Development of a platform for securing interoperability between components in a carbon-free island microgrid energy management system	Hwang J., Oh Y.-S., Song J.-U., An J.-G., Jeon J.-H.	2021	-	x	x	[80]
17	An interoperable communication framework for grid frequency regulation support from microgrids	Tightiz L., Yang H., Bevrani H.	2021	-	x	x	[33]
18	Interoperability analysis of IEC61850 protocol using an emulated IED in a HIL microgrid testbed	Hemmati M., Palahalli H., Gruosso G., Grillo S.	2021	x	x	x	[34]
19	Prototyping Multi-Protocol Communication to Enable Semantic Interoperability for Demand Response Services	Galkin N., Yang C.-W., Nordstrom L., Vyatkin V.	2021	-	x	x	[35]
20	A Multi-Site Networked Hardware-in-the-Loop Platform for Evaluation of Interoperability and Distributed Intelligence at Grid-Edge	Essakiappan S., et al.	2021	x	x	x	[61]

TABLE 7. ***(Continued.)*** **All Reviewed documents selected through database search and citation search.**

21	Implementation of resilient self-healing microgrids with IEC 61850-based communications	Hong J., Ishchenko D., Kondabathini A.	2021	x	x	x	[79]
22	Integration of SCADA Services and Power-Hardware-in-the-Loop Technique in Cross-Infrastructure Holistic Tests of Cyber-Physical Energy Systems	V. H. Nguyen, T. L. Nguyen, Q. T. Tran, Y. Besanger and R. Caire	2020	x	x	-	[36]
23	Communication requirements in microgrids: A practical survey	Serban I., et al.	2020	x	x	-	[62]
24	Control of Grid Frequency under Unscheduled Load Variations: A Two Layer Energy Management Controller in Urban Green Building's	Bramareswara Rao S.N.V., Padma K.	2020	x	x	-	[63]
25	Real-time monitoring and control of a microgrid - Pilot project: Hardware and software	Hosseinzadeh N., Mousavi A., Teirab A., Varzandeh S., Al-Hinai A.	2019	x	x	-	[64]
26	Fractal IoT: A scalable IoT framework for energy management in connected buildings	Anjana M.S., Ramesh M.V., Devidas A.R., Athira K.	2019	x	x	-	[74]
27	Modeling and integrating PV stations into IEC 61850 XMPP intelligent edge computing gateway	Liu C.-H., Gu J.-C.,	2019	-	x	x	[37]
28	Chalmers Campus as a Testbed for Intelligent Grids and Local Energy Systems	Antoniadou-Plytaria K., et al.	2019	x	x	-	[65]
29	Integration of SCADA services in cross-infrastructure holistic tests of cyber-physical energy systems	Nguyen V.H., Lam Nguyen T., Tran Q.T., Besanger Y., Caire R.	2019	-	x	x	[66]
30	A review on DC microgrid control techniques applications and trends	Bharath K.R., Krishnan Mithun M., Kanakasabapathy P.	2019	x	x	x	[25]
31	Considerations on Communication Infrastructures for Cooperative Operation of Smart Inverters	Dos Santos Alonso A.M., Afonso L.C., Brandao D.I., Tedeschi E., Marafao F.P.	2019	x	x	x	[55]
32	The IEC 61850 sampled measured values protocol: Analysis, threat identification, and feasibility of using NN forecasters to detect spoofed packets	Hariri M.E., et al.	2019	x	x	x	[38]
33	Lessons learned from microgrid implementation at electric utility	Vukojevic A.	2018	x	x	-	[39]
34	A Negotiation Cloud-based Solution to Support Interoperability among Interconnected Autonomous Microgrids	Cretan A., Coutinho C., Bratu B., Jardim-Goncalves R.	2018	x	x	-	[40]
35	Ontological Formulation of Microgrid Control System for Interoperability	Ingalalli A., Kumar R., Bhadra S.K.	2018	x	x	x	[41]
36	Remote Microgrid control center case study: Large-scale integration challenges	Al-Emam M.A., El-Sayed M.E., Resch J.G.	2018	x	x	x	[67]
37	Multi-agent system with plug-and-play feature for distributed secondary control in microgrid—controller and power hardware-in-the-loop implementation	Nguyen T.-L., et al.	2018	-	x	x	[24]
38	TOOCC: Enabling heterogeneous systems interoperability in the study of energy systems	Teixeira B., et al.	2017	x	x	-	[68]
39	Towards the next generation of smart grids: Semantic and holonic multi-agent management of distributed energy resources	Howell S., Rezgui Y., Hippolyte J.-L., Jayan B., Li H.	2017	x	x	x	[42]
40	Interoperability and interchangeability for microgrid protection systems using IEC 61850 standard	Ustun T.S.	2017	-	x	x	[23]
41	Development of middleware applied to microgrids by means of an open-source enterprise service bus	Rodríguez-Molina J., Martínez J.-F., Castillejo P., Rubio G.	2017	-	x	x	[43]
42	Integration of sensors, controllers and instruments using a novel OPC architecture	González I., Calderón A.J., Barragán A.J., Andújar J.M.	2017	x	x	-	[44]

TABLE 7. *(Continued.)* **All Reviewed documents selected through database search and citation search.**

43	RSE's microgrid: A facility for research development and testing of future distributed generation and microgrid technologies	Sandroni C., et al.	2016	-	x	x	[69]
44	Architecture and implementation of microgrid controller	Starke M., et al.	2016	x	x	-	[70]
45	Performance monitoring of a PMU in a microgrid environment based on IEC 61850-90-5	Kumar S., Das N., Islam S.	2016	-	x	x	[72]
46	Multiagent-based decentralized operation of microgrids considering data interoperability	Cintuglu M.H., Mohammed O.A.	2015	-	x	x	[71]
47	An integrated utility microgrid test site ecosystem optimized by an open interoperable distributed intelligence platform	Vukojevic A.; Laval S.; Handley J.	2015	x	x	-	[45]
48	IEEE 1547 Standards Advancing Grid Modernization	Basso T., Chakraborty S., Hoke A., Coddington M.	2015	-	x	x	[46]
49	Application of IEC61850 in energy management system for microgrids	Mao M., Mei F., Jin P., Chang L.	2014	-	x	x	[47]
50	Interoperability and interchangeability considerations in microgrids employing IEC61850 standard	Ustun T.S., Hadbah A., Kalam A.	2013	-	x	x	[48]

TABLE 8. **Additional documents included through citation searching.**

ID	Title	Author	Year	Type	Contribute to			Ref
					RQ1	RQ2	RQ3	
51	Solar Appliance Technology Brief: Interoperability	Efficiency for Access	2021	Report	x	x	x	[11]
52	Standards and Interoperability of Equipment and Systems for Smart Grid in India	Jindal, A., Bansal, M., & Kumar, A.	2020	Conference paper	x	x	x	[26]
53	Framework and Roadmap for Smart Grid Interoperability Standards Regional Roundtables Summary Report	Gopstein A., Nguyen C., Byrnett D.S., Worthington K., Villarreal C.	2020	Report	x	-	x	[49]
54	Defining a Microgrid Using IEEE 2030.7	Danley, D. R.	2019	Report	x	-	x	[50]
55	Recommendations for Trust and Encryption in DER Interoperability Standards	Obert J., et al.	2019	Report	x	-	x	[51]
56	Communication in Microgrids	Avendaño JLS, Martín LSM	2019	Book chapter	x	x	-	[52]
57	CIM and OPC UA for interoperability of micro-grid platforms	Nguyen V.H., Besanger, Y., & Tran Q.T.	2016	Conference paper	x	x	-	[53]
58	IEEE 1547 and 2030 standards for distributed energy resources interconnection and interoperability with the electricity grid	Basso, T.	2014	Report	x	-	x	[54]
59	Methodologies to facilitate Smart Grid system interoperability through standardization, system design, and testing	CEN-CENELEC-ETSI Smart Grid Coordination Group	2014	Report	-	x	x	[22]

AUTHOR CONTRIBUTION

Amalia Suryani contributed to conceptualization, methodology, data curation, investigation, formal analysis, visualization, writing the original draft, review, and editing. Ilman Sulaeman (IS) contributed to conceptualization, methodology, writing, review, and editing. Oo Abdul Rosyid contributed to the investigation, writing, review, and editing. Niek Moonen contributed to conceptualization, supervision, review, and editing. Jelena Popovićcontributed to conceptualization, methodology, supervision, review, and editing. All authors read and approved the final manuscript.

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AMALIA SURYANI received the B.Sc. degree in statistics from the Institute of Technology Sepuluh Nopember (ITS), Indonesia, the M.Sc. degree in environmental and energy management from the University of Twente, The Netherlands, and the joint master's degree in sustainable development from Leipzig University, Germany, and the University of Graz, Austria. She is currently pursuing the Ph.D. degree with the Faculty of Electrical Engineering, Mathematics, and Computer Science, University of Twente, The Netherlands, within the Accessible, Natural, Renewable, Growth, and Interaction (ANRGI) Project.

She was an Analyst with the Indonesian Ministry of Energy and Mineral Resources and Clinton Foundation, and the Project Manager for the Energising Development (EnDev) Program, Gesellschaft für Internationale Zusammenarbeit (GIZ), German Agency for International Cooperation. She has more than 12 years of working experience as an advisor and consultant in the renewable energy and energy access sectors. Her interest is in interdisciplinary studies that address societal challenges from a socio-technical standpoint. Her research interests include co-creation for the development and adoption of technological innovations in energy access.

ILMAN SULAEMAN received the bachelor's degree in electrical power engineering from Bandung Institute of Technology (ITB), Indonesia, in 2013, and the master's degree in sustainable energy technology from Delft University of Technology, The Netherlands, in 2016. He is currently pursuing the Ph.D. degree with the Power Electronics and Electromagnetic Compatibility Group, University of Twente, The Netherlands, with the Accessible, Natural, Renewable, Growth, and Interaction (ANRGI) Project.

From 2017 to 2020, he was with PT Syntek Energy and Control and has been involved in energy audits, feasibility studies, interconnection studies, and front-end engineering design of renewable energy-based power plants. His main objective is to increase energy access in remote areas and a reduction of waste of energy. His research interest includes electromagnetic interference in off-grid systems with a special interest in power quality improvement and immediate power balancing. He is a member of the IEEE Electromagnetic Compatibility Society TC7 on low-frequency EMC. He received the Indonesia Endowment Fund for Education (LPDP) Scholarship for the master's degree.

OO ABDUL ROSYID received the B.Sc. degree in physics from Padjadjaran University, Bandung, Indonesia, in 1990, the M.Sc. degree in renewable energy from the Carl von Ossietzky University of Oldenburg, Germany, in 1996, and the Dr.-Ing. degree in processing engineering from the Otto-von-Guericke University of Magdeburg, Germany, in 2006.

From 1991 to 2021, he was a Researcher with the Indonesian Agency for the Assessment and Application of Technology (BPPT). He is currently affiliated with the National Research and Innovation Agency (BRIN), Jakarta, Indonesia, contributing to the advancement of research and innovation in the field of renewable energy. Apart from his contributions to academia, he has published numerous papers, including Performance and Reliability of PV Modules in Indonesia (International Conference Proceeding of EU PVSEC, in 2023), Marine-Based Renewable Energy Solution for 3T Areas in Indonesia: Integrating Diesel Hybridization with Floating PV Power Plant (The 4th ICMMBT International Conference Proceeding, in 2023), and Design of Solar Water Pump System Using Pumping and Gravity Methods to Improve Human Living Standards in Hatuermera-Timor Leste (*The Report Seabold Journal*, in 2023). His research interests include the reliability and performance of PV modules and systems, the development and innovation of battery energy storage systems for PV systems, and the feasibility study and development of floating PV systems.

Dr. Rosyid holds memberships at the International Electrotechnical Commission (IEC) for the Solar Energy System as an Expert Member of the IEC TC-82, the National Technical Committee (NTC) for the Indonesian National Standard (SNI) as the Chairperson in the field of Solar Energy, and the Indonesian Solar Energy Association (AESI). His commitment to excellence has been recognized through the Herudi Technical Committee Award (HTCA), the Satyalancana Development Honorary Sign, the Satyalancana Wira Karya Honorary Sign, and the Satyalancana Karya Satya Honorary Sign.

NIEK MOONEN (Member, IEEE) received the B.Sc. degree in advanced technology, the M.Sc. degree in electrical engineering, and the Ph.D. (cum laude) degree in electromagnetic compatibility from the University of Twente, Enschede, The Netherlands, in 2012, 2014, and 2019, respectively.

Since 2019, he has been with the Power Electronics and Electromagnetic Compatibility Group, University of Twente, first as a Senior Researcher and currently as an Assistant Professor. His research interests include electromagnetic interference (EMI) mitigation in power electronics with a special interest in EMI propagation in smart grids, digital signal processing in electromagnetic compatibility measurements, and EMI filter optimization. He is a member of the IEEE Electromagnetic Compatibility Society TC7 on low-frequency EMC, IEEE PELS Society TC11 on aerospace power, TC12 on energy access and off-grid systems, and a Board Member of the Dutch EMC-ESD Association.

JELENA POPOVIĆ (Member, IEEE) received the Dipl. Ing. degree from the Faculty of Electrical Engineering, University of Belgrade, Serbia, and the Ph.D. degree from Delft University of Technology, Delft, The Netherlands.

She has experience working in academia, an industrial network, a start-up, and the government. She is currently with the University of Twente as an Associate Professor and Netherlands Enterprise Agency as an Energy Access Advisor. She has published more than 100 publications in scientific journals, magazines, and conferences. She has coauthored strategic research agendas, technology roadmaps, and white papers in energy access, power electronics, energy efficiency, and solid-state lighting. Her recent research interests include bottom-up solutions for energy access, appropriate technology, and socio-technical integration.

Dr. Popović is the Global Chair of IEEE Empower a Billion Lives, a global competition that fosters innovation toward universal energy access, and the Vice-Chair of the IEEE PELS Technical Committee TC-12 Energy Access and Off-Grid Systems.