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Billanes, Joy Dalmacio; Jorgensen, Bo Norregaard; Ma, Zheng Grace

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Improving Resilience and Sustainability: A Review of Ad-Hoc Microgrids' Operations' Strategies and Methods

Joy Dalmacio Billanes
SDU Center for Energy Informatics,
The Maersk Mc-Kinney Moller
Institute, The Faculty of Engineering,
University of Southern Denmark
Odense, Denmark

Bo Nørregaard Jørgensen
SDU Center for Energy Informatics,
The Maersk Mc-Kinney Moller
Institute, The Faculty of Engineering,
University of Southern Denmark
Odense, Denmark

Zheng Grace Ma*
SDU Center for Energy Informatics,
The Maersk Mc-Kinney Moller
Institute, The Faculty of Engineering,
University of Southern Denmark
Odense, Denmark

Abstract—**Ad-hoc microgrids are portable energy systems deployed in transportation to provide emergency electricity in areas affected by extreme events or attacks, thereby improving power supply flexibility and resilience. Despite their potential advantages, there is limited research available on ad-hoc microgrids, resulting in gaps in our understanding of their types and functions. This study conducts a review of subcategories, components, operational methodologies, and emerging patterns within ad-hoc microgrids, drawing from the scientific literature. Ad-hoc microgrids, though less extensively studied, exhibit adaptability, diversity, and operational efficacy across various conditions. Ad-hoc microgrids extend beyond load restoration, encompassing aims such as decreasing greenhouse gas emissions, enhancing energy access, and bolstering reliability, resilience, security, efficiency, and economic efficiency across various settings, including urban transportation networks. Finally, these insights deepen understanding of ad-hoc microgrid dynamics, offering support for future research endeavors, and facilitating practical implementations aimed at fostering more resilient and sustainable microgrid networks.**

Keywords—Ad-hoc microgrids, mobile microgrids, microgrids, operation strategies, resilience

I. INTRODUCTION

The occurrence of widespread power outages within the energy system is attributed to the increasing frequency of extreme weather events like typhoons, earthquakes, and floods, terrorism and cyberattacks, etc. [1],[2],[3],[4]. To address significant blackouts, it is necessary to coordinate various energy resources to restore power to essential services and infrastructure. Microgrids have emerged as a practical solution for promoting energy systems that can function autonomously or connected to the main grid [5],[6],[7]. Moreover, there's increasing attention towards utilizing mobile energy sources to help restore power during grid disruptions [8],[2].

Ad-hoc microgrids are a type of microgrid typically installed in transportation systems to provide emergency electricity in areas impacted by extreme events and attacks. The concept of an ad-hoc microgrid, often equated with a mobile microgrid in literature, is a transportable energy system that includes Mobile Energy Storage (MES) units [8], also referred to as 'storage-on-wheels' [1]. These systems can enhance flexibility, resilience, and reliability in energy supply, proving beneficial in various scenarios, including temporary power provision and emergency response following extreme events [4],[9]. For instance, studies indicate that electric vehicles, functioning as portable battery energy storage systems, can relocate and distribute energy across different locations [9]. However, the deployment of truck-mounted batteries to augment microgrid resilience, by strategically supplying energy to outage-affected areas, is impeded by significant capital investment requirements [9].

While traditional microgrids and ad-hoc microgrids share the fundamental objective of enhancing energy resilience and reliability, they differ significantly in several dimensions. Traditional microgrids are generally designed for semi-permanent installations with consistent and predictable operational parameters [14]. In contrast, ad-hoc microgrids are characterized by their mobility and rapid deployment capabilities, often required to function in highly variable and unpredictable environments, such as during natural disasters or cyber-attacks [15]. The system components of ad-hoc microgrids are tailored for portability and flexibility. Ad-hoc microgrids are designed for rapid integration into disrupted energy systems to provide immediate relief [16]. They can operate independently or with the main grid but are optimized for emergency deployment. Traditional microgrids, in contrast, are part of long-term strategies to enhance grid resilience and lack rapid deployment capabilities.

Both microgrid types rely on advanced digital technologies for operation and management, but ad-hoc microgrids face unique challenges in robustness and reliability under extreme conditions. Despite some literature has focused on ad-hoc microgrids' operational and technological aspects, there is a need for an in-depth understanding of their varying operational strategies and integration challenges. This paper aims to address this gap by analyzing the distinct features, challenges, and integration strategies of ad-hoc microgrids, providing insights to optimize their design and operation for enhanced resilience and sustainability in diverse scenarios.

The paper is organized as follows: Section II describes the literature review method. Section III provides data analysis and findings, while Section IV presents the discussion. Finally, conclusions are made and potential areas for future work are discussed in Section V.

II. METHODOLOGY

The literature review focuses on investigating the discussed operation management systems and operation strategies for ad-hoc microgrids, especially the operation management systems and operation strategies for resiliency.

The search string for ad-hoc microgrid:

("Ad hoc" OR Ad-hoc OR mobile OR Temporary OR Emergen*) AND (microgrid) AND (Operat* OR Optimi* OR

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Control OR Dispatch* OR Schedule* OR Strateg* OR Manag* OR Plan*) AND (Resilien* OR Robust* OR Flex* OR “Demand response” OR Adapt*)

To comprehensively review the literature in energy engineering, a thorough search was carried out across three bibliographic and full-text databases: IEEE Xplore, Web of Science, and Scopus. The inclusion of Scopus and Web of Science was driven by their broad coverage across various academic fields. Furthermore, IEEE Xplore was chosen for its relevance to the domains of computer science and engineering. The search was conducted in September 2023, with few restrictions imposed such as limitations on document types (journal paper, conference paper, and book chapters) and language. To facilitate the search, we utilized a clearly defined and organized search strategy based on keywords aligned with the research questions of this scoping review. These search terms revolved around concepts such as Ad-hoc, operation management, and resiliency. In total, 38 references were gathered from Web of Science (10), IEEE Xplore (16), and Scopus (12).

To enhance the clarity of the literature search, removing duplicates is necessary. To do that, using the Endnote integrated duplicate removal feature, references were compared one by one and decided which to keep. There were 26 duplicates were removed leaving us with 13 references. Afterwards, while screening if there are any references with missing information, additional duplicates were detected. To thoroughly remove duplicates, we undertook a manual screening by comparing critical attributes such as title and author. Some articles have similar titles but different types of paper, that’s why the document type, volume, pages and DOI were also screened. References with missing abstracts were filled and will be utilized in the next phase. For the remaining references, an abstract-based screening is conducted. 4 articles have been excluded from the Ad-hoc microgrid group, primarily due to their abstracts being unrelated to the search keywords. Consequently, a total of 8 references are retained.

III. RESULTS

Eight reviewed articles published between 2019 and 2023 have discussed the concept and operations of ad-hoc or mobile microgrids. A mobile or ad-hoc microgrid can be managed in various ways, for example, using transportation for energy storage systems to store and manage energy in the microgrid. In addition, the articles also described the different types of energy resources and energy storage systems installed in ad-hoc or mobile microgrids.

This section presents the analysis results of ad-hoc microgrids, and the discussion can be divided into four aspects:

- Microgrid setup
- Microgrid operations
- Microgrid performance
- Applied methods

A. Ad-hoc Microgrid setup

There are three types of ad-hoc microgrids (as shown in TABLE I): mobile energy resources (e.g., [2]), mobile microgrids (e.g., [4], [10]), and marine microgrids (e.g., [11],[12]). Microgrids with mobile energy resources are the most popular ad-hoc microgrids, and the mobile energy resources refer to energy storage in all the reviewed articles [2],[1],[8],[13], within the ad-hoc microgrids. For example, mobile microgrids are portable or mobile power systems [4] and they can operate in stand-alone mode or connected to the main grid [10]. Meanwhile, another type of ad-hoc microgrids is marine microgrids which can be hybrid shipboard microgrids [11] and Mobile Marine Microgrids (MMGs) [12].

TABLE I. AD-HOC MICROGRID TYPE

Ad-hoc microgrid type	References
Microgrids with mobile energy resources	[1], [2], [13], [8]
Mobile microgrid	[4], [10]
Marine Microgrids	[11], [12]

There are seven types of energy resources in ad-hoc microgrids mentioned in the reviewed articles including electric vehicles (EVs), Photovoltaic systems (PVs), wind turbines, energy storage systems, gas turbines, diesel generators, and sea wave energy as shown in TABLE II. Meanwhile, all the ad-hoc microgrids have two or more than two types of energy resources. Ad-hoc microgrids usually integrate Distributed Energy Resources (DERs) such as solar PVs (e.g., [4], [10], [11] and [12]) and wind turbines (e.g., [10], [11] and [12]) to facilitate energy accessibility, reduce cost, and reduce emission [10]. Stationary and mobile energy storage systems, such as battery storage systems[10] and electric vehicles (EVs), can also be integrated into all ad-hoc microgrids. Furthermore, ad-hoc microgrids also utilize EVs as mobile energy storage systems (MESS) [8] and can be integrated into urban transportation infrastructure [4]. While the Energy Storage Systems (ESS) (e.g., Battery Energy Storage Systems (BESS), flywheel energy storage system (FESS)) are deployed on marine microgrids operating in islanded mode [11]. Diesel generators and sea wave energy are the other energy sources that can integrated into ad-hoc microgrids [12], [13], [11].

TABLE II. AD-HOC MICROGRID COMPONENTS

Ad-hoc microgrid components	References
Energy storage	[1], [2], [4], [13], [8], [10], [11]
PV	[4], [13], [10], [11], [12]
Wind	[10], [13], [11],[12]
EV	[4], [13]
Diesel generator	[12], [13], [11]
Gas turbine	[12]
Sea Wave Energy	[11]

B. Ad-hoc Microgrid operations

Ad-hoc microgrids operating in normal and extreme conditions as well as during disturbance or uncertainty were investigated as shown in TABLE III. In normal operation conditions, ad-hoc microgrids operate in a steady state or in a predictable state in day-ahead or real-time operations [4]. For instance, during normal conditions, ad-hoc microgrids utilize mobile storage systems like Electric Vehicles (EVs) to charge energy during low-demand hours and discharge energy during peak-demand hours [13]. In addition, Ad-hoc microgrids can utilize Mobile Energy Storage (ES) units to conduct spatio-temporal energy arbitrage under normal operating conditions [1]. Meanwhile, during extreme events such as disasters and disturbances, ad-hoc microgrids can restore loads [2] and can utilize public transportation routes to move the mobile energy storage (ES) [1]. A study also reveals that Ad-hoc microgrids can prepare for extreme events by evaluating worst-case scenarios and understanding potential costs and challenges [13]. Ad-hoc microgrid studies also highlight operational approaches that can adapt and respond to uncertainties [8], [10], disturbances [10], and power disruptions [8].

TABLE III. AD-HOC MICROGRID OPERATION CONDITIONS

Operation conditions	**References**
Normal	[1], [4], [13], [10], [12]
Extreme events	[1], [2], [4], [13], [12]
Disturbance/ Uncertainty	[8], [8], [10]

The operations of ad-hoc microgrids encompass dispatch, standalone operation, grid connectivity, frequency control, critical service restoration, and demand response. Concerning dispatch, TABLE IV emphasizes several aspects of managing energy resources within an Ad-hoc microgrid. The reviewed literature indicates that ad-hoc microgrid operations strategy focuses on the coordination of resources and scheduling of energy storage systems [8], [2]. Dispatch also involves optimization of investments, and strategic deployment of energy storage [1] to enhance resilience and avoid disruptions, particularly during disasters. Moreover, Ad-hoc microgrids can operate in standalone or grid-connected mode [10] Literature reviewed reveals different operation strategies related to grid connection. For instance, a study employs Plug and Play strategies to simplify the interconnection process among nomadic communities, with the main grid, and among themselves [10]. An additional illustration includes a study highlighting grid-connected microgrids with renewables [13], along with a separate study that employs the integration of Security Constraint Unit Commitment (SCUC) and Mobile Marine Microgrids(MMMGS) to the coastal distribution grids [12].

Furthermore, the reviewed literature also underscores frequency control as an operational strategy in a shipboard microgrid to manage loads and balance power consumption and generation [11]. In addition, a study discusses the deployment of a mobile microgrid through Urban Transportation Networks (UTN) and the utilization of a Critical Service Restoration (CSR) strategy to restore critical loads in areas like hospitals, police and fire stations during extreme events [4]. Finally, Risk-Based Demand Response (RBDR) as an operation strategy, entails adjusting electricity usage in response to potential risks, specifically considering factors such as electricity prices and market uncertainties [13].

TABLE IV. AD-HOC MICROGRID OPERATION STRATEGIES

Ad-hoc Microgrid operation strategies	**References**
Dispatch	[2], [1],[8]
Stand-alone mode	[10]
Connect to the main grid	[13], [10], [12]
Frequency Control	[11]
Critical service restoration	[4]
Demand Response	[13]

C. Ad-hoc Microgrid performance

The literature reviewed highlights that ad-hoc microgrids' studies target goals related to climate and environment; social and cultural; technology as well as economic and financial aspects (as shown in TABLE V). In climate and environment, Ad-hoc microgrids are concerned about reducing greenhouse gas emissions in the power systems of the ship [11]. Concerning social and cultural performance, a study in Mongolia aims at improving energy access in nomadic communities [10]. In terms of technological aspects, the literature reviewed focuses on enhancing reliability, resilience, security, and efficiency. Resilience is the ability of the grid to prepare, adapt, withstand, and recover quickly from to changing conditions and extreme outages [4]. For instance, a study highlights the enhancement of reliability, resilience, and security of an Active Distribution Network (ADN) within the context of a constrained Urban Transportation Network (UTN) both in normal steady state and extreme conditions [4]. In addition, studies in ad-hoc microgrids seek to improve the resilience within the microgrids [2], and distribution systems [1], as well as the security of the coastal distribution grids [12]. Reviewed literature also revealed the importance of critical load restoration [8], and improving efficiency of energy supply management within the microgrid [11]. In addition, the reviewed literature also highlights the focus on economic and financial aspects by improving the economic efficiency within microgrids[13]. For example, improving the efficiency of Active Distribution Network (ADN) considering the challenges and limitations posed by the constrained Urban Transportation Network (UTN) [4].

TABLE V. AD-HOC MICROGRID PERFORMANCE DIMENSION

Ad-hoc Microgrid performance dimension	**References**
Climate and environment	[11]
Social and cultural	[10]
Technological	Reliability [4] Resilience [1],[2],[4],[8],[12] Security [4],[12] Efficiency [11]
Economical and financial	[4], [13]

D. Applied methods for Ad-hoc microgrids

Different methods are applied to enhance the performance of ad-hoc microgrids and are divided into five purposes (as shown in TABLE VI). Ad-hoc microgrids apply methods for analyzing; designing and planning; verification or validation; decision-making; and optimization. Deep Reinforcement Learning is one of the utilized methods in ad-hoc microgrids [10]. It is a technique for designing and planning energy supply systems in rural and isolated areas, particularly for nomadic communities, as it helps address uncertainties and complex conditions. Real options theory is also utilized to analyze the values of flexibility and plug-and-play operation [10].

Meanwhile, to enable the verification and validation of specific aspects of the ad-hoc microgrid systems' performance and efficiency, methods such as Hardware-in-the-Loop (HIL) simulation and numerical simulation were used (shown in Table 6). Hardware-in-the-Loop (HIL) Simulation is applied to evaluate how well a model-free nonlinear sliding mode controller can manage and stabilize load frequency within a shipboard microgrid [11], while the numerical simulation is used to confirm the positive economic effectiveness of energy storage systems within Ad-hoc microgrid [13]. Decision-making methods such as Novel Hierarchical and Hybrid Multi-agent Reinforcement Learning (MARL) to solve the Decentralized Partially Observable Markov Decision Process (Dec-POMDP) [2] and Security Constraint Unit Commitment (SCUC) to optimize the power system while considering security constraints when scheduling the operation of generators [12].

Ad-hoc microgrids may undergo optimization through various methods, including the Mixed-Integer Non-Linear Programming (MINLP) model, Deep Reinforcement Learning, heuristic technique, Progressive hedging algorithm, and model-free nonlinear sliding mode controller as shown in Table 6. A mixed-Integer Non-Linear Programming (MINLP) model based on the General Algebraic Modeling System (GAMS) software package is utilized to create a more detailed and adaptable optimization approach [13]. Deep Reinforcement Learning could be applied to address problems related to optimal scheduling in uncertain environments [8]. Meanwhile, Collective Decision Optimization Algorithm (CDOA) could be used to address issues related to the electricity flow in a power system [12]. Moreover, the optimization of mobile Energy Storage (ES) unit deployment and utilization can be achieved through the application of the Progressive Hedging Algorithm [1]. In the Shipboard Microgrids (MGs), a model-free nonlinear sliding mode controller is utilized to maintain a balance between consumption and power generation [11]. The enhanced version of this controller is introduced specifically for secondary load frequency control [11]. The performance of the optimized modified model-free nonlinear sliding mode controller is improved through the application of a hybrid algorithm that combines the Sine-Cosine Algorithm and Wavelet-Mutation (SCAWM) [11].

TABLE VI. APPLIED METHODS

Applied method	References
Analysis	[10]
Design and Planning	[10]
Verification and Validation	[13],[11]
Decision Making	[2], [12]
Optimization	[1], [13], [8], [12], [11]

IV. DISCUSSION

The study aims to review and analyze the existing literature on ad-hoc microgrids. Specifically, focuses on identifying the sub-types, components, performance focus, operation strategies, and methods applied within ad-hoc microgrids. Collecting literature on ad-hoc microgrids posed difficulties. Potential explanations for the scarcity of studies on ad-hoc microgrids could stem from a lack of recognition of it as a separate research area or perhaps because ad-hoc microgrids are still in their nascent phases of development.

Ad-hoc microgrids encompass various sub-types, including mobile energy resources, mobile microgrids, and marine microgrids. Key components of ad-hoc microgrids include electric vehicles, photovoltaic systems, wind turbines, energy storage systems, gas turbines, diesel generators, and sea wave energy. These microgrids are designed to perform under both normal and extreme conditions, managing disturbances and uncertainties effectively. Under normal circumstances, ad-hoc microgrids utilize mobile storage systems for optimal energy management. During extreme events, these systems focus on load restoration and employ public transportation routes for the relocation of mobile energy storage.

Operational strategies in ad-hoc microgrids include dispatch, standalone operation, grid connectivity, frequency control, critical service restoration, and demand response. The performance of ad-hoc microgrids is driven by goals related to climate, social, technological, and economic aspects, such as reducing emissions, improving energy access, enhancing reliability and security, and optimizing economic efficiency. Methodologies applied within ad-hoc microgrids include Deep Reinforcement Learning, real options theory, verification and validation techniques, decision-making methods, and optimization approaches to address various challenges.

Ad-hoc microgrids are integral to localized and decentralized energy systems. These systems, while often smaller and more flexible than traditional power systems, are designed to provide reliable electricity in areas where traditional infrastructure is unavailable or impractical. However, their reliance on digital technologies and communication systems makes them vulnerable to cyber threats, including cyber-attacks, sensor malfunctions, and the introduction of false data. Studies reviewed in this analysis emphasize the need for resilient techniques to address stability and reliability concerns within microgrids.

One critical aspect of ad-hoc microgrids is their ability to operate autonomously or in conjunction with the main grid. Effective control and optimization strategies are essential to enhance the performance and resilience of these systems. For example, dispatch strategies in ad-hoc microgrids involve coordinating and scheduling energy storage systems to optimize investments and strategic deployment, particularly during disasters. Techniques such as Mixed-Integer Non-Linear Programming (MINLP) and Deep Reinforcement Learning create adaptable optimization approaches for scheduling and resource management in uncertain environments.

Frequency control is another significant operational strategy, particularly in shipboard microgrids, to manage loads and balance power generation and consumption. Advanced controllers, such as model-free nonlinear sliding mode controllers, maintain stability and improve load frequency control. The integration of hybrid algorithms combining the Sine-Cosine Algorithm and Wavelet-Mutation (SCAWM) shows promise in enhancing the performance of these controllers.

The sustainability implications of ad-hoc microgrids are multifaceted. These systems provide reliable electricity in areas where traditional infrastructure is unavailable, enhancing energy access and promoting environmental sustainability. By integrating renewable energy sources such as solar photovoltaics (PVs) and wind turbines, ad-hoc microgrids contribute to reducing greenhouse gas emissions and facilitating a cleaner energy supply. For instance, integrating Distributed Energy Resources (DERs) like solar PVs and wind turbines helps reduce costs and emissions while improving energy accessibility.

However, the development and deployment of ad-hoc microgrids face regulatory and policy challenges. Imbalances in policies and regulations related to microgrid development can hinder their widespread adoption and implementation.

Addressing these regulatory barriers is crucial for fostering an enabling environment for the growth of ad-hoc microgrids. Policymakers need to consider the unique requirements and potential benefits of these systems to create supportive frameworks that encourage innovation and investment in microgrid technologies.

Overall, the findings underscore several key areas for future research and development that could be explored to address the challenges and optimize the roles of ad-hoc microgrids in the evolving energy landscape, including advanced control and optimization strategies to enhance the performance and resilience of ad-hoc microgrids; dedicated exploration of advanced cybersecurity solutions tailored to the unique characteristics of ad-hoc microgrids; supportive regulatory frameworks to encourage the development and deployment of ad-hoc microgrids.

V. CONCLUSION

This study provides a detailed review and contribute to a better understanding of the complex aspects of the ad-hoc microgrid. It examines the microgrids' operational strategies, and diverse approaches for its implementation, as well as the various simulation methods employed for evaluating the effectiveness of the proposed approaches. Compared to previous studies, this research offers a more comprehensive analysis of operational strategies across different types of microgrids, demonstrating a unique focus on resilience in the face of natural disasters and cyber threats. This study demonstrates that ad-hoc microgrid objectives go beyond load restoration, including goals such as reducing greenhouse gas emissions, improving energy access, and enhancing reliability, resilience, security, efficiency, and economic efficiency within diverse contexts like urban transportation networks.

Finally, this scoping review contributes valuable insights to the current understanding of microgrids, emphasizing the need for further research and development to address challenges and optimize their roles in the evolving energy landscape. However, the study acknowledges limitations in its geographical focus and the range of technologies considered, suggesting future research could expand on these aspects. Overall, this study serves as a basis for future research and practical implementations related to ad-hoc, community, and networked microgrids. The insights provided are intended to offer direction to different stakeholders such as researchers, policymakers, and industry stakeholders, with the goal of advancing towards a more resilient and sustainable energy system.

To enhance the practical relevance and impact of future studies, there is a need for in-depth investigations into the application of advanced control and optimization strategies for ad-hoc microgrids. The growing concern over cybersecurity also demands a dedicated exploration of advanced cybersecurity solutions, tailored to the unique characteristics of ad-hoc microgrids.

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