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Review Article

A Systematic Review of Challenges in the Implementation and Integration of Decentralized Microgrids

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Abstract *- Decentralized microgrids are necessary for global decarbonization, making the grid more resilient and expanding universal access. But a complicated web of interconnected challenges makes it very hard for them to be widely commercialized. This systematic review thoroughly examines these deployment challenges within technical, economic, social, environmental, and policy frameworks. While employing dual-lens analytical methodology, 105 peer-reviewed publications and reports published from 2014 onwards were aggregated from ScienceDirect, Google Scholar, and Academia. The results show that complicated inverter control requirements, non-detection zones in islanding, and power quality degradation make it much harder to deploy technology. The high upfront capital costs of battery energy storage systems and the lack of local peer-to-peer electricity marketplaces make it hard for local residents to make investments, especially in low-income areas. To promote real energy democracy, social integration needs to get past behavioral resistance, "NIMBYism," and a history of uncertainty in institutions. The unsustainable mining of vital minerals and the impending catastrophe of technological waste create significant ecological contradictions. Also, old, centralized regulatory frameworks and the absence of common interoperability standards make these administrative problems much worse. A cross-regional analysis reveals significant geographic disparities: Europe and North America focus on the digital integration of prosumers and the reinforcement of legacy grids against severe weather, whereas emerging economies in Africa and South Asia contend with fundamental rural electrification amid inadequate infrastructure. This assessment provides a strategic path to fill these research gaps. It focuses on AI-driven predictive controllers, circular economy frameworks for batteries that have already been used, and the harmonization of grid codes around the world.*

Keywords *- Decentralized microgrids, Distributed energy resources, Energy policy, Grid resilience, Renewable energy integration.*

1. Introduction

Modern power systems are changing from centralized, fossil-fuel-dependent generation to sustainable, low-carbon, and highly distributed architectures [1]. The main reasons for this change are the urgent need to lower greenhouse gas emissions, make energy more secure, and make the environment more sustainable on a global scale. The use of decentralized microgrids, which are localized groups of distributed energy resources (DERs), energy storage systems, and interconnected loads that work together as one controllable unit, is at the heart of this change [2]. Microgrids are an important way to connect renewable energy sources, such as solar and wind, directly to local distribution networks. When managed correctly with advanced controllers, localized generation reduces transmission losses and eases the strain on older macrogrids [3]. However, this benefit is not automatic. Without proper synchronization and smart inverter technology, connecting intermittent renewable sources can actually destabilize weak distribution networks rather than supporting them.

Even though these decentralized microgrids have some structural advantages, putting them together creates a lot of technological problems. Modern microgrids, on the other hand, rely primarily on inverter-based generating [4]. This is different from traditional power grids, which depend on the huge rotating inertia of heavy synchronous machines to keep things stable. Renewable sources like solar Photovoltaic (PV) and wind are quite unreliable since they depend on changing weather conditions.

This makes the electricity output very inconsistent. This inconsistency has a direct effect on the quality of power in the microgrid, causing voltage sags, frequency deviations, and harmonic distortion [5]. To make these networks stable, complicated power electronics and extra management systems are needed to keep the phases in sync all the time, especially when a microgrid disconnects from the main grid to work in autonomous island mode [6].

These technical problems are made much worse by the fact that different regions are very different from each other. For instance, in Sub-Saharan Africa, getting more people access to energy is still a big problem, with millions still not having dependable electricity [7]. Decentralized microgrids are a good way to bring electricity to rural areas where it is either expensive or too far away to extend the national utility system [8]. But in places like Nigeria, where there are abundant solar resources, these hybrid off-grid systems are not always reliable because the distribution infrastructure is inadequate and there are few conventional technical frameworks [9].

In South and Southeast Asia, rapid economic growth has also led to a rise in energy consumption, but the region's sensitivity to climate change means that coal use must quickly be phased out. Microgrids are being promoted in island nations to make power generation more decentralized, yet these areas have major problems with their infrastructure. The slow adoption of modern energy management systems and the lack of strong regulatory frameworks make it harder for community-level smart grids to grow. This makes it harder for the region to reach its goal of net-zero emissions [10].

Economic hurdles are also a big reason why decentralized microgrids are not being used more. Getting smart inverters, transformers, and large-scale battery energy storage systems requires a lot of capital up front, which is a big problem, especially for poor towns and developing economies [11]. Although renewable microgrids offer low long-term operational costs, their prohibitive initial capital requirements severely restrict accessibility. These problems are made worse by a lack of financing choices, high borrowing rates for independent power producers, and tariff structures that are too strict and out of date. This makes it hard to get a consistent return on investment [12].

The lifecycle of the technologies that make up microgrids also influences the environment. It is true that decentralized renewable energy is cleaner than relying on fossil fuels, but the significant reliance on energy storage, especially lithium-ion and lead-acid batteries, has a big impact on the environment. The resource extraction needed to make batteries, along with the paucity of recycling facilities for electronic trash and old panels, raises serious questions about the long-term sustainability of these localized power systems [13].

Finally, the way people think about and accept localized energy systems in society and politics is another challenge. For community microgrids to work, the public needs to be involved and share power [14]. Projects often run into problems with people's behaviour because they do not know enough about the technology, there are disagreements about how to use the land needed for localized PV farms, and community members have different financial interests. Without strong, all-encompassing legislative frameworks, social apathy can stop engineering efforts that are otherwise technically sound [15].

The existing literature on distributed energy generation often focuses on isolated problems. For example, many studies exclusively examine specific inverter control strategies or assess the financial viability of microgrids within a single developed nation. Consequently, current research often fails to provide readers with an adequate background on how these challenges intersect. A distinct research gap exists because prior studies rarely demonstrate how technical engineering constraints are tied to economic limitations and regulatory frameworks. Additionally, many papers group all microgrids together without defining clear boundaries between grid-connected urban systems and completely off-grid rural networks.

To address these limitations, the scope of this study is strictly confined to decentralized, inverter-based renewable microgrids. The novelty of this work stems from its application of a comparative classification framework. Rather than merely cataloging challenges, this paper categorizes them into five specific areas: technical, economic, social, environmental, and policy. Using this framework, the review evaluates how these five barriers affect four distinct regions (Africa, Asia, Europe, and the Americas). By directly comparing the digital integration issues in Europe with the fundamental rural electrification deficits in Africa, this paper provides a more realistic and comprehensive perspective than previous reviews.

2. Review Methodology

2.1. Literature Search and Selection Criteria

To build the foundation for this review, literature was gathered from three academic databases. ScienceDirect was used to find research on power electronics and grid integration. Google Scholar helped locate global case studies and energy policy discussions, while Academia provided access to engineering conference proceedings. The search relied on specific keyword strings, such as "decentralized microgrids," "microgrid integration challenges," and "distributed energy regulatory barriers."

Strict inclusion and exclusion criteria were applied to keep the review focused. Included studies had to be peer-reviewed, published in English, and directly related to decentralized or off-grid microgrid integration. The timeframe was restricted to publications from 2014 onward to ensure the discussed technology was current. Papers were excluded if they were not peer-reviewed, focused only on traditional macrogrid transmission, or relied on outdated technology. A small exception was made for five foundational studies published before 2014 to provide necessary background context.

2.2. Quality Assessment and Publication Bias

Before including a paper, its methodology and relevance were evaluated. However, it is important to note potential publication bias in this review. Because the search was limited to English-language publications, valuable insights from non-English case studies, especially localized reports from emerging economies in Latin America and francophone Africa, may have been missed. Also, successful microgrid projects are more likely to be published than failed ones, which can skew the available literature toward positive engineering outcomes. After the final screening, the selected literature was organized to evaluate the data across the five thematic barriers and four geographic regions.

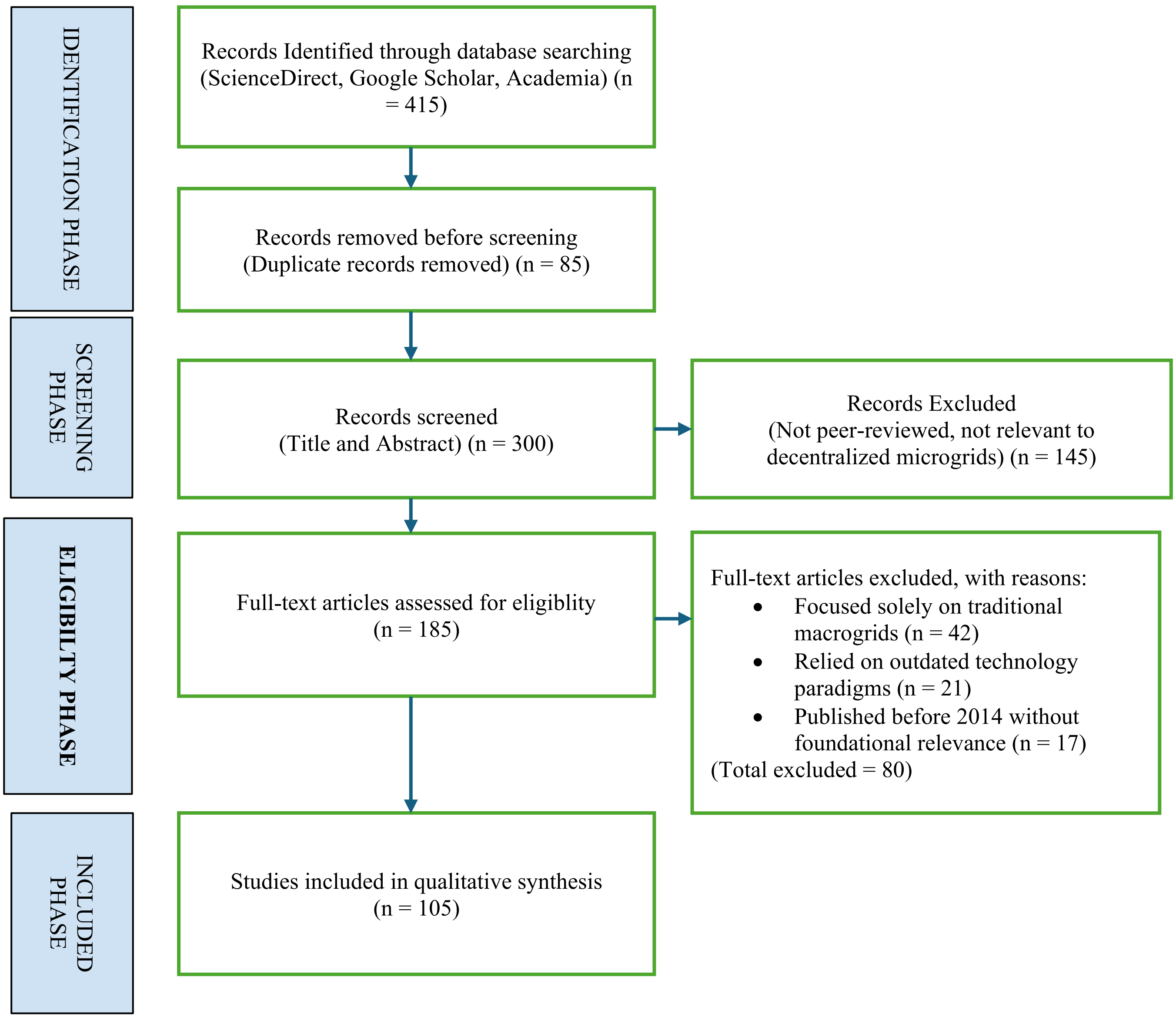

Fig. 1 The PRISMA Diagram

3. Review of Related Works

3.1. Global Overview

The global energy environment is currently undergoing an extraordinary transformation, driven by an increasing transition toward decentralized power systems and the digitalization of energy infrastructure [16]. The worldwide market used to be dominated by huge, centralized fossil fuel generation. Now, it is quickly moving towards Distributed Energy Resources (DERs), with localized energy markets and decentralized microgrids as the building blocks of this new way of distribution [17]. International agreements to reach carbon neutrality are a big part of this change. To do this, emissions must be cut down on a vast scale in all areas of life, including homes, businesses, and industries [18].

Recent worldwide data show that the world's energy system is quickly becoming more electric. The use of modern meta-heuristic optimization techniques has helped microgrids all over the world deal with the fact that renewable energy sources are not always available. This has lowered operating costs and increased energy output [19]. The investigation of novel zero-carbon energy carriers, including the direct incorporation of green hydrogen generation into local power systems, is enhancing the operational efficiency of microgrids, facilitating increased energy autonomy and long-term storage capacity [20].

As far as technology goes, the worldwide conversation about deploying microgrids has changed from basic electrical integration to the strategic management of digitally enhanced energy networks. Advanced machine learning techniques for predictive maintenance and sophisticated Energy Management Systems (EMS) to autonomously balance supply and demand are becoming more common in modern microgrid systems around the world [21, 22]. Also, Virtual Power Plants (VPPs) are being used more to link together several microgrids in the same area. This makes a strong technological platform that controls energy production and use on a large scale [23].

These ongoing improvements in power electronics, hybrid designs, and smart grid optimization make it possible to control energy dispatch in real time, allow power to flow both ways without any problems, and improve coordination between localized generation and the main utility grid [24]. So, microgrids are no longer just seen as backup systems for emergencies; they are now seen as permanent, smart ways to distribute electricity and make the grid more resilient [25].

3.2. Thematic Barriers

The implementation of decentralized microgrids, while holding significant promise for improving energy resilience and sustainability, is hindered by a complex array of difficulties. These constraints are not independent; they are intricately linked, affecting engineering hardware, financial markets, human behaviour, ecological consequences, and legal structures.

To give a structured and thorough look at these problems, this section divides these challenges into five main thematic barriers: technical, economic, social, environmental, and policy. To provide a complete picture, each of these thematic sections explores not only the specific barriers themselves, but also the broader impacts they cause and the frameworks required to overcome them. By analyzing these variables separately, a more lucid comprehension of the systemic challenges hindering global microgrid integration can be attained.

3.2.1. Technical Barriers

Switching from centralized synchronous generation to decentralized microgrids creates very complicated technological problems, mostly because of the strong reliance on power electronics and inverter-interfaced distributed energy resources (IIDERs). One of the biggest problems is that inverters need to be controlled very carefully to keep the voltage and frequency stable [26]. Microgrid inverters do not have any built-in rotational mass, unlike standard heavy rotating equipment that gives the grid natural physical inertia. To artificially stabilize the network, advanced primary and secondary control techniques are needed, such as voltage/frequency (V/f) droop control and active/reactive power (P/Q) sharing [27]. However, it is still a big engineering challenge to make strong controllers that can handle bidirectional power flow without any problems while working in both grid-connected and isolated modes. To keep the system from crashing when the load changes, these controllers often need complicated, microcontroller-driven algorithms [28]. This complexity is further exacerbated in DC microgrids, where voltage interfacing across several power conversion stages necessitates precisely synchronized bidirectional converters to properly control energy storage [29].

Another important technical problem is finding and dealing with islanding modes accurately. Unintentional islanding happens when a microgrid gets cut off from the main utility grid, but local distributed generators keep the local network powered. If this state is not found quickly, it might harm equipment badly, put utility workers' safety at risk, and cause re-closure that is not in sync [30]. There are several ways to detect Islanding Detection Methods (IDMs), and they can be divided into passive, active, hybrid, and remote methods. However, many of them have a major problem with the "Non-Detection Zone" (NDZ). In this area, the protective relays cannot find the grid disconnection if the power difference between the local generation and the load is close to zero [31]. Active approaches, like the Sliding Mode Frequency Shift (SMFS), try to push the frequency out of range to trigger detection; this makes the power quality of the microgrid worse by nature [32]. Recent advancements suggest employing machine learning frameworks, such as Random Vector Functional Link Networks (RVFLN), to dynamically monitor harmonic distortions and swiftly identify islanding under various conditions [33]. However, the establishment of universally acceptable NDZ limits that adhere to stringent grid codes continues to pose a regulatory and technical challenge [34].

Another common technical problem is that power quality gets worse. When microgrids switch from being connected to the main grid to being isolated, the lack of strong voltage support from the main grid can cause big power imbalances and voltage changes. The fact that renewable sources are only available at certain times, along with the inverters' switching frequencies, causes a lot of harmonic distortion in the network

[35]. These problems show up as voltage sags, frequency changes, and uneven voltage balancing, all of which can shorten the lifespan of sensitive load equipment and energy storage batteries by a large amount. Microgrids must follow strict grid rules to properly connect to the larger Electrical Power System (EPS). These codes usually require a Voltage Unbalance Factor (VUF) of no more than 2% to 3% [36].

Finally, protecting microgrid architectures is a big change from how we safeguard regular power systems. Centralized synchronous generators provide large short-circuit fault currents to quickly trip overcurrent relays in traditional radial distribution networks [37]. Inverter-interfaced microgrids, on the other hand, significantly limit fault current contributions to safeguard their fragile semiconductor switches. They usually only give 1.1 to 2 times the rated current. This low fault current "blinds" standard protective relays, which means they either do not work at all or do not work fast enough during a fault [38]. One of the biggest technical challenges to widespread use of microgrids is coming up with an adaptive protection scheme that can tell the difference between a grid-connected fault (which has high fault currents) and an islanded fault (which has low fault currents), while also taking into account bidirectional power flows and changing network topologies [38].

3.2.2. Economic Barriers

The long-term operational costs of decentralized energy based on renewables are naturally low, but the economic barriers to starting up a microgrid are still one of the biggest problems in the world. The main financial problem is that the system's basic infrastructure needs a lot of money to build (CAPEX). Microgrids need a lot of money up front for modern power electronics, Intelligent Electronic Devices (IEDs), smart meters, and, most importantly, Battery Energy Storage Systems (BESS) [24]. This is different from standard grid extensions, which only need transmission lines and step-down transformers. Even though the prices of solar photovoltaic modules are going down, buying high-capacity energy storage and bidirectional smart inverters still makes the system cost more at first. This often makes the Levelized Cost of Energy (LCOE) less competitive in the short term compared to heavily subsidized centralized fossil-fuel generation [39].

These capital limitations are particularly severe in emerging economies. For example, financial models for off-grid projects in Sub-Saharan Africa often assume high upfront capital costs based strictly on the import prices of smart inverters and lithium-ion batteries. However, these models rarely account for local currency devaluation or the low purchasing power of rural communities [40]. Even with a solid technical design, a microgrid project often fails to launch simply because the end-users cannot afford tariffs that reflect the true cost of the imported hardware [18]. Also, Independent Power Producers (IPPs) have a hard time getting low-interest loans for projects that are not connected to the grid. Local banks sometimes see decentralized energy projects as high-risk because there is no past performance data. This leads to high financing rates and demands for too much collateral, which slows down project development [17].

Unpredictable Operational Expenditure (OPEX) has a big effect on the economic feasibility of microgrids, in addition to the initial CAPEX [41]. Renewable resources like solar and wind do not cost anything to use, but keeping the complicated mechanical and electronic parts in good shape is a major challenge, especially battery storage systems, which are highly susceptible to thermal degradation, resulting in substantial recurring replacement costs [22]. If an inverter breaks down or a battery bank wears out faster than expected because of poor localized energy management, the expenses of replacing them might cause a massive reduction in the project's profits. New machine learning frameworks for predictive maintenance look promising for reducing these kinds of unanticipated operational failures, but adding these kinds of advanced diagnostics involves more initial investment than many project developers are not prepared to do [21].

Lastly, the lack of strong, localized electricity markets makes it very hard to predict how much money will come in. For grid-tied microgrids to be financially sustainable, they must be able to sell extra power back to the main utility grid or trade energy directly with other microgrids. But microgrid operators typically can not take part in energy markets because of rigid pricing structures, unclear Feed-in Tariffs (FiTs), and utility restrictions that support one company over another [19]. The Return On Investment (ROI) is still low due to high installation costs and the lack of dynamic revenue streams. This means that many microgrid initiatives are limited to grant-funded pilot programs instead of being able to grow into commercial reality.

3.2.3. Social Barriers

There is a lot of information about the engineering and economic problems that come with decentralized microgrids, but the social and technical problems are often not given enough thought, which can cause projects that are otherwise technically sound to fail. The change from a centralized power grid to a decentralized microgrid changes the role of the end user in a big way. People who use electricity are no longer just passive users; they are now expected to become "prosumers" who actively take part in local energy generation, use, and peer-to-peer sharing [42].

This change in thinking needs a lot of community involvement, yet a lack of technical knowledge and a resistance to change often slow down adoption. People in communities generally do not trust microgrid projects because they do not understand how smart meters and bidirectional inverters work. They worry that they may lose control over their energy use or have to pay unexpected costs [43].

The problem of trust and institutional legitimacy is a big societal barrier. In many developing countries and rural areas, centralized utility firms have historically left people out, which makes them very wary of new energy developers. When outside contractors or government organizations try to build community microgrids without first having open conversations with the community, people typically see the projects as top-down impositions instead of communal assets [44]. This absence of "energy democracy" may provoke significant resistance. To get people to accept the microgrid socially and politically, it is important for them to be actively involved in its development, governance, and ownership structures [45]. The microgrid project could make social disparities worse if people in the community don't feel like they own it or if the financial benefits are not shared fairly among inhabitants. This is a concept that is becoming more common in literature as a failure of "energy justice" [46].

Additionally, physical and aesthetic issues, often called the "Not In My Back Yard" (NIMBY) phenomenon, make it hard for the local population to generate renewable energy in their own neighborhoods. Microgrids usually require major infrastructure, including extensive arrays of solar PV panels, wind turbines, and big battery storage units, within or adjacent to residential areas. However, these deployments frequently encounter local resistance driven by concerns over land-use conflicts, visual degradation, and acoustic disturbances from backup diesel generators and wind turbines [47].

Lastly, the issue of complicated community dynamics cannot be ignored. A decentralized microgrid requires an agreement on how to share energy, when to cut back on power use when generation is low, and the responsibility for maintenance. When it comes to fairly sharing generated electricity, there are always disagreements, especially in off-grid rural networks where energy resources are quite limited. To deal with these complicated social issues, developers need to involve sociologists and community leaders in the engineering planning phase. This will make sure that the technology design fits with the cultural and social practices of the end users [48].

3.2.4. Environmental Barriers

The main reason for adopting decentralized microgrids is to reduce GreenHouse Gas (GHG) emissions and get rid of fossil fuels. However, putting these systems in specific places can create big environmental problems. A significant contradiction in the renewable energy transition is that, although the operational phase of solar and wind power is "clean," the entire lifecycle of the necessary hardware, from raw material extraction to end-of-life disposal, has substantial ecological impacts [49].

The biggest environmental problem with microgrid architecture is that it depends too much on Battery Energy Storage Systems (BESS) to make up for the fact that renewable energy sources are not always available. To make lithium-ion, lead-acid, and new solid-state batteries, a lot of mining of limited, important raw materials, including lithium, cobalt, nickel, and rare earth elements, is needed [50]. These minerals are very energy-intensive to extract, and mining areas often have serious soil degradation, water table contamination, and localized toxic emissions [51].

Also, the end-of-life management of microgrid parts is a growing environmental problem, especially in developing countries where recycling infrastructure for electronic trash (e-waste) is very weak or non-existent. When solar Photovoltaic (PV) panels, smart inverters, and high-capacity battery banks stop working, they create millions of tonnes of complicated e-waste [52]. This usually happens after 10 to 20 years of use. Toxic heavy metals from broken batteries and broken semiconductor switches could leak into landfills if there are no closed-loop material recovery systems. Research into "second-life" battery uses, such as recycling deteriorated electric vehicle batteries for stationary microgrid storage, offers promise for extending the usefulness of hardware. However, the need to eventually dispose of the batteries is still an inescapable environmental problem [53].

Disruptions to the environment and space are also major problems. Utility-scale microgrids, especially those that rely significantly on solar and wind turbines, need a lot more area than centralized fossil-fuel facilities that use a lot of electricity. Putting up these large arrays can cause big changes in how land is used, break up habitats, and move local wildlife [54]. In rural and ecologically vulnerable places, removing land for localized energy generation might, ironically, make it harder to protect the environment.

Lastly, there is a need to discuss how hybrid microgrids work in actual life. In many developing areas where the cost of battery storage is still too high, decentralized microgrids commonly work as hybrid systems, using backup diesel or natural gas synchronous generators to keep the voltage stable when renewable energy is low for long periods of time. These hybrid systems use less fuel overall, but the backup generators still release localized particulate matter and nitrogen oxide (NOx) emissions that are bad for the environment and public health in the areas around them [55].

3.2.5. Policy Barriers

The policy and regulatory frameworks governing decentralized microgrids have not kept up with the rapid progress of engineering solutions for them. Historically, electricity legislation in both established and emerging nations was based on a centralized, monopolistic paradigm for generating and distributing power. The shift to a decentralized paradigm breaks apart this old regulatory system, making the legal environment very unclear and making it very hard to establish microgrids [56].

One of the main problems with policy is that there is no clear legal definition for microgrids and their management. In a lot of places, energy law does not officially recognize "prosumers" (those who buy and sell power) or community energy clusters as separate groups. As a result, localized energy communities typically have to deal with the same complicated licensing, tax, and compliance rules that were created for huge, utility-scale power facilities [57]. This mismatch in regulations makes it impossible for small independent power producers and community cooperatives to get their projects approved and raises legal costs [58].

Also, the fact that state-owned or legacy utility firms have a monopoly on the market typically makes it harder to integrate microgrids. To get the most out of a microgrid's economic efficiency, operators need to be able to sell extra power to the main utility grid or trade energy with other networks directly (P2P). But current rules often make it illegal for third parties to sell electricity or limit access to the grid, which means that microgrids have to work in complete isolation all the time. Even when grid-tied operation is allowed, microgrid developers cannot count on steady income because there are no standardized, clear Feed-in Tariffs (FiTs) or net-metering laws [60].

Another big problem with policy is that there are no globally accepted technical standards and grid codes. While engineers have developed advanced inverters and protective relays, connecting these components remains difficult due to a lack of standardization [61]. This interoperability issue exists on two distinct levels: physical hardware standards, such as uniform voltage ratings and plug-and-play connections, and software communication protocols, such as common data models that allow smart meters to talk seamlessly with utility networks. Both must be addressed for microgrids to scale efficiently. Regulatory agencies frequently encounter difficulties in formulating standardized grid codes that delineate precise power quality measures (including voltage imbalance and harmonic distortion thresholds) and islanding detection techniques essential for microgrid connections. Without unified national and international standards, developers must create custom control systems for each project to meet local rules that are not consistent, which means they cannot take advantage of economies of scale [62].

Lastly, to make the transition fair, there is a need for proactive policy tools that support "energy democracy." However, current governance models often do not do enough to encourage fair deployment. Legislative frameworks frequently do not include specific subsidies, tax credits, or risk-mitigation assurances intended to facilitate microgrid adoption in low-income or marginalized rural regions [63]. Because of this, advanced smart grids are mostly being built in rich areas or commercial industrial parks. Areas that are suffering from severe energy poverty still have to rely on old, unreliable centralized infrastructure. To get over these policy barriers, the way the electrical market is set up needs to be completely changed. Instead of strict, top-down rules, there should be more flexible, decentralized rules [64].

To quickly summarize the interconnected obstacles discussed in the preceding sections, Table 1 outlines the primary barriers hindering decentralized microgrid deployment, their main implications, and the regions most heavily affected.

Table 1. Summary of Microgrid Integration Barriers

Barrier Theme	Primary Challenge	Key Implication	Primary Regional Context
Technical	Inverter phase synchronization and islanding non-detection.	Degraded power quality and network instability.	Global (Most severe in weak grids)
Economic	High upfront capital expenditure (CAPEX) for batteries.	Unaffordable energy tariffs for local end-users.	Developing economies
Social	Lack of technical trust and land-use disputes (NIMBYism).	Project delays or complete community rejection.	Developed economies
Environmental	Heavy reliance on mining for lithium and lead-acid batteries.	E-waste accumulation and ecological damage.	Global
Policy	Absence of unified grid codes and interoperability standards.	Prevents peer-to-peer trading and system scaling.	Global

3.3. Regional Analysis

The thematic barriers described in the previous section give a basic idea of the larger problems that come with deploying microgrids, although these problems do not happen in the same way all over the world. The severity, magnitude, and prioritization of these barriers are significantly influenced by unique geographic limitations, socio-economic inequalities, and past utility infrastructures. For example, the engineering effort required in a highly industrialized, legacy-grid setting is very different from that needed for off-grid rural electrification. This section offers a comparative geographical analysis, scrutinizing the distinct trajectories and localized impediments in Africa, Asia, Europe, and the Americas, to demonstrate how particular geographic contexts influence the decentralized energy revolution.

3.3.1. Africa

The main reason for adopting decentralized microgrids in Sub-Saharan Africa (SSA) is very different from the main reason in the global north. Developed countries mostly use microgrids to make the grid more reliable and reduce carbon emissions from existing infrastructure. In SSA, the main goal is to make energy more accessible. Around 75% of the world's population that do not have electricity lives in SSA right now. More than 500 million people do not have access to reliable power, mostly in rural and isolated places [65]. Because it costs too much to connect national utility grids across large, sparsely inhabited, and rough terrain, off-grid hybrid renewable mini-grids have become the most cost-effective way to bring electricity to rural areas [66].

Even though there is a lot of promise, structural economic and technical constraints make it very difficult to set up decentralized energy systems across the continent. The biggest problem is the high initial cost of solar Photovoltaic (PV) arrays and Battery Energy Storage Systems (BESS). For instance, in West Africa, rural consumers have very little money to spend, which makes cost-reflective tariffs politically sensitive and often too expensive for the end user without a lot of government support [67]. As a result, independent power producers have a hard time getting long-term loans with reasonable interest rates since local commercial banks often see off-grid rural projects as risky investments [68].

The operational environment in Africa presents distinct engineering challenges. In Nigeria and other nations where weak current distribution networks make centralized generation very difficult, off-grid and hybrid mini-grids are becoming more and more popular as the best answer. But keeping the power quality up to par in these small networks is still a big problem.

The addition of intermittent solar PV to these fragile rural systems typically causes significant voltage sags and harmonic distortion [69]. This is because they do not have dynamic compensation technologies like D-STATCOMs or modern smart inverters to control voltage. Also, the very high temperatures in SSA speed up the breakdown of lead-acid and lithium-ion batteries, which raises the project's operating and maintenance expenses over time [70].

Lastly, policy fragmentation is still a major problem. Many African countries have set high goals for renewable energy, but the rules for mini-grid licensing, peer-to-peer tariff structures, and grid-arrival compensation (what happens to an off-grid developer when the national grid finally arrives) are still very unclear [71]. Pilot projects that were heavily funded by international donors have worked well in places like Tanzania and Kenya, but moving from small pilot projects to widespread, commercially viable deployment needs a big change in regional energy policies and strong support from institutions [7, 8, 72].

3.3.2. Asia

In Asia, the use of decentralized microgrids is motivated by a unique duality: the necessity to support growing industrialization and economic complexity while still keeping strict international carbon reduction commitments [73]. Asia has a unique problem: it needs to move away from its long-standing reliance on coal while also dealing with the rapid growth in energy demand from cities that are growing quickly [74]. Because of this, people in this area do not just see microgrids as backup systems for rural areas; they see them as necessary, localized structures for switching to 100% renewable energy systems without losing industrial output.

In East Asia, especially in China, the main focus is on optimizing technology and integrating microgrids into the market. The Chinese government has heavily subsidized the installation of solar photovoltaic (PV) generation, which has led to a move toward community-level energy storage systems. However, a significant challenge persists in achieving an equitable distribution of revenues between microgrid developers and local residents [75]. To address these financial challenges, China has been the first to combine park microgrids with medium- and long-term green electricity trading markets. These localized industrial park microgrids can dynamically estimate spot market prices using complex multi-objective optimization algorithms. This helps the purchase of power in the most efficient way possible, which greatly reduces the carbon footprint [76]. Additionally, the quick rise in popularity of Electric Vehicles (EVs) in East Asia adds another level of difficulty. To successfully integrate these EVs into microgrids, which use Vehicle-to-Grid (V2G) technology as mobile energy storage, strong carbon trading systems and complicated operation scheduling are needed to avoid overloading the grid in some areas [77].

In South Asia, on the other hand, the structural constraints are quite similar to those in Sub-Saharan Africa, but the overall grid penetration is higher. One of the main goals of deploying microgrids in nations like India and Pakistan is to stabilize supply in areas that have a lot of load shedding and huge transmission losses. The South Asian Association for Regional Cooperation (SAARC) has looked into the idea of turning broken smart grids into "super smart grids" that are connected to each other in order to balance supply and demand in the area [78]. But this change is being held back by the fact that renewables do not always function, there are no uniform net-metering laws, and managing bidirectional power flows across old, unstable distribution networks is a difficult problem.

Geographical limitations in Southeast Asia completely change the energy transition. Indonesia and the Philippines are examples of archipelagic nations. They are made up of thousands of distant islands where it is not logistically or economically possible to develop centralized national grids through underwater cables [8]. As a result, isolated microgrids are the only way to get electricity to everyone. Researchers are increasingly looking into how to add localized Wave Energy Converters (WECs) to islanded microgrids to help solar PV during the monsoon seasons, given the long coasts [80].

Peer-to-Peer (P2P) energy resource sharing is the most important change in rural Southeast Asian electrification. Decentralized mesh-grids let prosumers (those who make more solar energy than they need) trade energy directly with their neighbors [81]. P2P sharing reduces dependence on centralized utilities and makes better use of costly battery storage. However, it is not widely used yet because there are not enough telecommunication technologies to support it, there are no regulatory frameworks in place, and the initial cost of smart metering is too high for low-income rural communities [82]. To get over these problems all throughout the continent, we need more than just government subsidies [83]. We also need a uniform regulatory framework that makes smart grid technologies the same everywhere and encourages localized energy markets [84].

3.3.3. Europe

The European energy landscape is very different from that of developing nations. It is made up of old power grids that are very reliable, easy to get to, and very connected. So, the main reason for decentralized microgrid deployment in Europe is not basic energy access, but rather a strong push for decarbonization, grid resilience, and making energy markets more open to everyone [85]. The European Union (EU) has tried to fundamentally change the role of the end-user by moving from a centralized utility model to a localized, prosumer-centric design. This is in line with the ambitious goals of the European Green Deal.

The “Clean Energy for All Europeans” package was the most important regulatory change that led to this change happening. It made the ideas of Renewable Energy Communities (RECs) and Citizen Energy Communities (CECs) legal [86]. These laws let people, local governments, and small businesses work together to invest in and run localized microgrids. But even with this overwhelming support from lawmakers, there are still big problems with the structure and administration. One of the biggest problems is turning these broad EU rules into national legislation that works together. Many member states still have trouble putting microgrid cooperatives into categories, even if historical grid operators and national regulatory bodies are trying to do so. These small community grids often have to follow the same difficult rules for licensing, balancing, and taxes that are meant for huge, national Distribution System Operators (DSOs) [87].

Europe has a unique problem with old infrastructure that is causing traffic jams. Because the European grid is already very full and substantially built, adding new, localized bidirectional power flows would need major improvements to grid intelligence [88]. European microgrids often use very complex digital twins, Virtual Power Plants (VPPs), and smart Internet of Things (IoT) sensors to deal with grid congestion and make it easier for people to trade energy with each other (P2P) [89]. But the installation of this modern smart metering system directly conflicts with strict European data privacy laws. The General Data Protection Regulation (GDPR) sets rigorous rules for how third-party aggregators can gather, send, and use customer energy data. This makes it hard for engineers to create localized, data-heavy energy management systems [90].

Lastly, the way European energy markets work makes it hard for microgrids to generate profits. The economic incentive for a community to run in autonomous “island mode” is low because centralized grid power is very reliable. European microgrids must instead generate profits by delivering extra services (like frequency regulation or peak shaving) back to the main utility grid. But because there are no standardized, cross-border flexibility markets, many microgrid operators cannot generate profits from these services, which limits their ability to grow beyond state-funded experimental projects [91].

3.3.4. The Americas

The installation of decentralized microgrids throughout the Americas highlights a significant disparity between the resilience-oriented markets of North America and the access-focused rural electrification issues in Latin and South America.

The main reason for the rise of microgrids in North America, especially in the US and Canada, is the need for the grid to be able to handle more extreme weather events [92]. Older centralized macrogrids have become more vulnerable to climate-related problems. Because of the constant threat of huge wildfires in California, utility companies have had to use Public Safety Power Shutoffs (PSPS), which deliberately cut off power to huge transmission lines. Because of this unreliability, many businesses and homes are using microgrids that rely on localized solar PV and battery storage to keep running when the grid goes down [93]. The catastrophic failure of Puerto Rico’s electrical grid after Hurricane Maria underscored the urgent need to shift from a fragile, centralized system to a robust network of interconnected, localized microgrids [94].

Even though technology is moving quickly, the US has big policy problems because of how different regulations are. Because the US does not have one clear national energy strategy, microgrid developers have to deal with a lot of different rules in each state. Unclear restrictions about selling energy to third parties, stringent limits on net metering, and the monopolistic defense of utility franchises sometimes make it hard for independent power producers to generate profits from microgrid assets, which slows down large-scale commercial implementation [95].

Extreme geographical limitations and socio-economic inequalities strongly influence the obstacles in South and Latin America. In Brazil and other countries, government-led efforts to bring electricity to more people face the huge logistical problem of extending transmission lines into the Amazon basin's dense, remote areas. In these faraway places, the only engineering option that works is off-grid hybrid microgrids. However, the expensive initial Capital Expenditure (CAPEX) of modern power electronics and the fact that it is hard to move replacement batteries across complicated river networks make the Levelized Cost of Energy (LCOE) much higher [96].

Heavy industry also plays a big role in energy transformation in South America. In places like Chile and Peru, the mining industry runs huge extraction operations in the Andes mountains, which are high up and far away. These processes need huge amounts of power that do not come from the national grid at all. Switching these remote industrial sites from heavy diesel use to renewable microgrids could greatly reduce carbon emissions, but it requires very strong, specialized inverter control strategies that can handle huge, changing industrial loads without the main grid's stiff voltage support [97].

3.4. Economic and Policy Frameworks

To successfully deploy microgrids on a global scale, the engineering solutions discussed earlier must be backed by highly structured economic and policy frameworks. From a financial perspective, relying strictly on international grants or short-term pilot funding is not sustainable for long-term commercial growth. Independent power producers and local developers require access to blended finance models and low-interest microloans. This is especially true in developing regions, where rural consumers lack the purchasing power to absorb the high initial Capital Expenditure (CAPEX) associated with large battery energy storage systems [40, 66]. A functional economic framework must shift the focus toward localized energy markets where prosumers can actively trade energy or sell excess power back to the national grid to generate a predictable return on investment [17].

On the regulatory side, these financial models will fail without clear, predictable policy frameworks. Governments must transition away from protecting centralized utility monopolies and instead establish standardized Feed-in Tariffs (FiTs) and transparent net-metering laws [60]. Furthermore, national energy policies need to legally recognize local energy cooperatives. Taking inspiration from the European Union's Renewable Energy Communities [86], creating unified legal definitions and standardized grid codes will give decentralized networks the administrative protection they require. This policy alignment allows small-scale developers to commercialize and scale their projects without facing overwhelming legal and licensing barriers.

3.5. Case Studies and Best Practices

Examining real-world deployments provides practical best practices for overcoming regional integration barriers. In North America, the primary driver for microgrid adoption is climate resilience. Following the catastrophic failure of Puerto Rico's macrogrid after Hurricane Maria, and the frequent Public Safety Power Shutoffs (PSPS) during the California wildfires, local developers successfully demonstrated the value of designing microgrids with prioritized autonomous islanding capabilities to protect critical infrastructure [93, 94]. The best practice established in these regions is the strategic shift from viewing microgrids as temporary emergency backup generators to treating them as permanent, localized resilience hubs.

In contrast, deployments in East Asia highlight best practices for digital market integration. Localized industrial park microgrids in China have successfully connected directly with green electricity trading markets. By using multi-objective optimization algorithms to estimate spot market prices, these facilities can dynamically purchase power to lower their regional carbon footprints while maintaining heavy industrial output [76].

Across all these varied geographical cases, the most consistent best practice is integrated socio-technical planning. Projects consistently succeed when advanced engineering designs are matched directly with local economic realities and transparent community governance [14, 48]. Failing to include the local population in the planning phase often leads to behavioral resistance, demonstrating that community ownership and education are just as important to the success of a microgrid as the physical hardware.

4. Discussion

This review's findings show that there are many constraints that make it hard for decentralized microgrids to be widely used in the technical, economic, social, environmental, and policy areas. Despite considerable engineering progress in distributed generation, notable deficiencies remain in these thematic domains and within the unique regional settings of Africa, Asia, Europe, and the Americas. This section puts all of these discoveries together, looks at worldwide trends that keep coming up, points out differences between regions, and finds areas that need more research.

Across the barriers that were discussed, there are a number of patterns that come up repeatedly. These themes show how intertwined the challenges are with decentralized energy adoption. Technical problems that affect all engineers include the fact that renewable energy sources are not always available, inverter-based generation doesn't have rotational inertia, and phase synchronization needs to be very precise. Developed areas, including Europe and North America, have made a lot of progress in using advanced smart grid technology, Virtual Power Plants (VPPs), and dynamic reactive power compensators to make these networks more stable. But in poor areas, old infrastructure and weak distribution networks still make microgrids less reliable and less scalable. These differences show how important it is to make targeted technological investments and share technologies in order to close the global engineering gap. This analysis reveals a stark divide between developed and developing regions, driven largely by existing infrastructure and capital access. In developed regions like Europe and North America, the macrogrid is already highly saturated.

The primary engineering goal is to integrate smart digital controllers to protect against severe weather and to allow active prosumers to trade energy. Funding is generally available, but rigid, outdated regulations slow down progress. Conversely, in developing regions across Sub-Saharan Africa and South Asia, the core goal is basic electrification. These areas struggle with severe infrastructure deficits and high interest rates on loans. While developed nations are optimizing advanced virtual power plants, developing nations are still working to subsidize the basic hardware costs of solar panels and batteries. This economic and technological gap shows that microgrid integration requires completely different strategies depending on the local economy.

Economic and policy hurdles are also intimately linked, since the speed of microgrid implementation depends on financial incentives and rules. In sophisticated markets, Feed-in Tariffs (FiTs) and green power trading have worked well to encourage localized energy production. However, there are questions about how long these systems will work in the market. Meanwhile, many developing countries still do not have access to new financial tools or low-interest finance. This is because Battery Energy Storage Systems (BESS) and smart inverters require a lot of capital to set up, which makes it difficult for the industry to grow. The biggest problem on a worldwide scale is making financial and policy systems that work well technically and are economically sound in quite different social and economic situations.

Social constraints, especially public acceptance and behavioral reluctance, make it even harder to switch to localized energy systems. The basic transition from passive consumer to active "prosumer" necessitates a significant degree of community involvement. In affluent areas, aesthetic concerns and land-use disputes (NIMBYism) commonly drive behavioural opposition. In developing areas, on the other hand, cultural hurdles, institutional distrust, and a lack of technical knowledge are more common. To get over these problems, we need to focus on public communication and energy governance that emphasize the real, local benefits of decentralized power systems.

Different regions have different problems with adopting microgrids, which shows how important it is to come up with engineering and policy solutions that work in each area. In Africa, problems are made worse by the fact that rural areas don't have enough electricity, and central networks are quite weak. [7] pointed out that millions of people still do not have reliable access to power, which is why off-grid hybrid mini-grids are the best way to go. [68] highlighted that without advanced dynamic compensating systems, adding intermittent solar to these weak networks will tend to reduce the power quality. Also, [76] said that the low buying power of rural customers makes it impossible to have cost-reflective pricing. To solve these problems, microgrid deployment needs to be a part of larger rural development projects, and strong, standardized technical frameworks need to be put in place to attract international financing.

Asia has a very heterogeneous environment. In East Asia, microgrid technology is moving quickly and is becoming more integrated with digital technology. In South and Southeast Asia, on the other hand, infrastructure problems are very serious. [76] highlighted that in China, adding industrial park microgrids to green power trading markets had worked to lower localized carbon footprints. On the contrary, [78] emphasized that in South Asia, the shift to interconnected smart grids is significantly obstructed by the intricate task of overseeing bidirectional power flows across deteriorating infrastructure. In archipelagic regions, [81] emphasized that although Peer-to-Peer (P2P) energy sharing presents significant opportunities for isolated communities, its implementation is hindered by the absence of facilitating connectivity technology. Creating unified legislative frameworks that standardize smart grid interoperability across the continent could greatly reduce these differences.

Europe is the world leader in the decentralized energy shift, but it has its own problems with policy harmonization and legacy grid congestion. [86] pointed out how important the EU's Clean Energy Package was in making Renewable Energy Communities (RECs) official. However, [87] stressed how hard it is for these small, localized cooperatives to follow national legislation that was made for big, centralized utility companies. Moreover, [88] emphasized that incorporating extensive networks of decentralized generation into Europe's densely populated macrogrid necessitates significant, data-intensive digital enhancements. This shows that we still need a single regulatory policy that works for tiny, local situations without putting the stability of the larger, densely connected continental grid at risk.

Lastly, in the Americas, microgrid use is limited by very difficult geography and a lack of clear policies. [92] emphasized that the main reason for deployment in North America is to make the grid more resilient to bad weather, but [95] stressed that differences in state-by-state regulations and utility monopolies are still getting in the way of widespread commercial scaling. At the same time, [96] said that in Latin America, bringing reliable power to remote, rough areas makes the Levelized Cost Of Energy (LCOE) too costly for off-grid businesses. To fix these two problems, there is a need to find a balance between the needs of local resilience and the need for flexible, cross-jurisdictional collaboration. This will make sure that decentralized energy is not only a privilege for rich businesses but a standard that everyone can use.

Compared to other literature reviews, which typically isolate specific engineering components, such as inverter topologies or localized economic models, this study achieves a more comprehensive synthesis. By cross-referencing technical constraints with socio-economic realities, this review moves beyond isolated technical reporting. It clearly demonstrates how non-technical barriers, such as fragmented policies and a lack of financing, actively prevent the deployment of state-of-the-art microgrid technologies, providing a much more realistic roadmap for future development.

5. Research Gaps

Even if decentralized microgrids are becoming more prevalent, there are still several important gaps in the areas of technology, economics, society, the environment, and politics. To overcome these challenges and make the switch to strong, localized energy systems as easy as possible, there is a need to address these gaps. The subsequent analysis systematically addresses these gaps, accompanied by integrated strategies to address them.

A significant technical gap persists due to the absence of universally accurate, non-intrusive islanding detection methods. Current active detection methods frequently encounter difficulties in identifying grid disconnections without deliberately compromising the power quality of the network. [33] emphasized the essential requirement for sophisticated detection systems utilizing Machine Learning (ML) frameworks, like Random Vector Functional Link Networks, to monitor harmonic aberrations dynamically. Creating and standardizing these AI-powered tools could get rid of Non-Detection Zones (NDZ) and make the grid more stable. Moreover, [28] underscored the enduring difficulty of flawless inverter regulation during mode transitions. More research into adaptive, grid-forming inverter topologies could make decentralized networks far more stable when they are changing.

Economic limitations, especially the volatility of Operational Expenditures (OPEX) and the insufficient utilization of localized energy trading systems, continue to pose a substantial challenge to the scalability of microgrids. [21] discovered that the lack of predictive maintenance frameworks is a big reason why costs are higher than predicted. They also said that scalable machine learning diagnostics are still not well-developed for small-scale microgrids. Adding cost-effective, cloud-based predictive maintenance solutions might save lifecycle expenses by a huge amount. Also, [17] said that local electricity markets and Peer-To-Peer (P2P) trading systems are conceptually attractive but not very useful in practice because there is not enough financial modelling. Creating adaptable micro-market models that use blockchain technology could give Independent Power Producers (IPPs) the financial stability required for investment.

Socio-economic differences further aggravate deployment challenges. [43] stressed that current research frequently concentrates on the technical performance of microgrids, overlooking the socio-economic aspects of "energy justice" and fair benefit distribution, especially for low-income populations encountering significant initial expenses. Targeted subsidies and easy-to-use microfinancing options can help include those who are currently left out, leading to much wider community adoption. People often do not give enough thought to how society will react to decentralized energy. [47] said that the interaction of emotional variables, like aesthetic concerns (NIMBYism) and lack of faith in institutions, is still not well understood. To get over these problems, there is a need to use community-led design methods that take into account local cultural preferences. Custom communication programs that focus on the short-term, concrete benefits of microgrids, like job development and grid autonomy, can greatly increase public support.

Another important topic that needs immediate attention is the environmental problems that come with the lifecycle of microgrid technology. [52] noted that current lifecycle assessments (LCAs) frequently lack precision for the end-of-life disposal of large battery energy storage systems (BESS), especially in developing areas devoid of electronic waste recycling infrastructure. Encouraging LCAs that are particular to certain areas and moving forward with circular economy frameworks for important minerals could help lessen these serious environmental effects. Also, [53] pointed out that there has not been enough focus on the environmental and economic sustainability of "second-life" batteries. To make sure that decentralized energy fits in with larger global environmental goals, there is a need to provide clear, standardized rules for properly recycling deteriorated electric vehicle batteries for stationary microgrid storage.

The lack of a unified policy is still a big problem for microgrid adoption. [57] stressed that there are no unified rules for putting community energy systems into legacy grid rules. Setting up international partnerships to standardize grid codes, interoperability criteria, and legal definitions could help bring these rules together and make it easier to follow them. [64] pointed out how very slowly prosumers and P2P networks are being added to current legal systems, which makes it very hard for localized energy innovation to happen.

Making rules easier to follow and offering fair, flexible pricing can encourage people in the community to get involved. Cross-regional studies that pinpoint optimal practices in decentralized governance and policy alignment are essential to developing more effective, scalable regulatory strategies.

6. Future Research Directions

Moving forward, the academic focus must shift away from isolated, small-scale technical simulations and move toward comprehensive, real-world deployment strategies. On the engineering front, future studies should prioritize the development of cost-effective, machine-learning-based predictive maintenance algorithms. While advanced diagnostic frameworks exist for utility-scale macrogrids, tailoring these systems for small-scale, decentralized battery networks will be highly necessary to reduce unexpected operational expenditures [21]. Additionally, researchers must focus on developing universally acceptable islanding detection methods that do not intentionally degrade power quality to operate effectively [33].

From an environmental standpoint, significantly more research is required regarding the lifecycle management of microgrid hardware. Current literature frequently overlooks the impending electronic waste challenges in developing regions that lack advanced recycling infrastructure [52]. Future studies should explicitly explore circular economy models, particularly evaluating the economic feasibility and safety standards for recycling degraded electric vehicle batteries for stationary microgrid storage [53].

Finally, addressing the socio-political gaps will require targeted research into energy justice. Future policy studies must develop adaptable, cross-border regulatory templates to help emerging markets scale their decentralized networks equitably. This research is necessary to ensure that low-income communities are not left entirely dependent on failing centralized grids while advanced smart-grid technologies are deployed only in affluent areas [46, 57].

7. Conclusion

The move toward decentralized microgrids is an important change in the design of power systems around the world that will help reduce carbon emissions, make the grid more reliable, and drive global electrification. This thorough research has shown, nonetheless, that the widespread use of these localized energy networks is limited by a complicated, highly interwoven network of technological, economic, social, environmental, and policy issues.

The transition from large synchronous generating to inverter-based distributed energy resources presents significant engineering hurdles. To keep the power quality high, it is necessary that the islanding transitions go smoothly, and developing adaptive protection methods requires advanced, digitally integrated control strategies. The high initial prices of Battery Energy Storage Systems (BESS) and smart grid infrastructure are still keeping investors away, especially in developing countries where financial institutions are still not very good. To make decentralized energy work, people need to be proactive and include everyone in the process. This will help get over behavioural reluctance, institutional distrust, and “NIMBYism,” making sure that energy transitions are fair. The lifetime effects of making parts and the growing problem of getting rid of electronic trash create an ecological conundrum that needs to be dealt with through strong circular economy frameworks. Lastly, outdated, centralized regulatory regulations, broken grid codes, and the absence of interoperability standards are still the biggest administrative problems that stand in the way of widespread commercialization.

The severity and prioritization of these barriers differ markedly across various geographic locations. In Sub-Saharan Africa and some parts of South Asia, the core goal must stay the same: to get basic rural electricity by fixing financial and infrastructure problems. On the other hand, in Europe and East Asia, the main problem is how to digitally connect decentralized generation to old, highly saturated macrogrids and make peer-to-peer energy markets more standardized. In the Americas, it is still very important to find a balance between the urgent need for localized climate resilience and the fact that utility rules are very different from state to state.

To get over these many kinds of barriers, there is a need to change the way the energy systems are designed, funded, and managed. Stakeholders can unleash the full potential of decentralized microgrids by encouraging collaboration between regions, making regulatory frameworks more consistent, encouraging fair funding methods, and continuing to make progress in machine learning and grid-forming technology. It is not just a technical goal to figure out how to deal with these interconnected problems; it is also a global necessity for ensuring a strong, fair, and long-lasting energy future.

Conflicts of Interest

The authors have no competing financial interests or personal ties to disclose that might have influenced the writing of this review.

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