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Emerging Trends, Opportunities, and Challenges of Renewable Mini-Grids of the Future

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الاتجاهات الناشئة والفرص والتحديات التي تواجه شبكات الطاقة الصغيرة المتجددة في المستقبل

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Abstract:
Renewable mini-grids are emerging as a vital solution for enhancing energy access, decarbonization, and resilience, particularly in remote and underserved regions. This paper explores key aspects shaping the future of renewable mini-grids, including emerging trends, opportunities, and challenges. One significant factor is the development of robust quality infrastructure (QI), which includes standards, testing, certification, and monitoring to ensure system reliability and mitigate deployment risks. Additionally, low-voltage direct current (LVDC) mini-grids are gaining traction due to their superior efficiency, simplified design, and reduced energy conversion losses. Opportunities abound in areas such as increased access to electricity, integration of distributed renewable energy resources, and sector coupling through advanced technologies like energy storage and peer-to-peer energy trading. However, various challenges persist, including regulatory uncertainty, high capital investment, technical issues related to system protection and integration, and limited compatibility of DC appliances. Addressing these challenges through policy reforms, technological advancements, and community engagement will be crucial to realizing the full potential of renewable mini-grids as sustainable energy systems of the future. To sum up, the levelized cost of electricity (LCOE) for autonomous basic service mini-grids ranged between USD 0.39 per kilowatt-hour (kWh) and USD 0.58/kWh, while autonomous full-service systems exhibited LCOE values ranging from USD 0.50/kWh to USD 0.75/kWh. These cost metrics demonstrate that mini-grids powered entirely by renewable energy represent a cost-competitive alternative to small gasoline and diesel generators, whose LCOE typically ranges from USD 0.35/kWh to USD 0.70/kWh.

Keywords: Renewable, Mini-Grids, Quality infrastructure, Low-voltage direct current.

الملخص
تظهر الشبكات المصغرة للطاقة المتجددة كحل حيوي لتعزيز الوصول إلى الطاقة، وإزالة الكربون، وزيادة المرونة، لا سيما في المناطق النائية والمحرومة. يستعرض هذا البحث الجوانب الرئيسية التي تشكل مستقبل الشبكات المصغرة للطاقة

المتجددة، بما في ذلك الاتجاهات الناشئة، الفرص، والتحديات. أحد العوامل المهمة هو تطوير بنية تحتية قوية للجودة (QI)، والتي تشمل وضع المعايير، والاختبارات، وشهادات الاعتماد، وآليات المراقبة لضمان موثوقية الأنظمة والتقليل من مخاطر النشر. بالإضافة إلى ذلك، تكتسب الشبكات المصغرة المعتمدة على التيار المباشر منخفض الجهد (LVDC) زخمًا نظرًا لكفاءتها العالية، وبساطة تصميمها، وانخفاض خسائر تحويل الطاقة. توجد العديد من الفرص الواعدة في مجالات مثل زيادة الوصول إلى الكهرباء، التكامل مع الموارد المتجددة الموزعة، وربط القطاعات المختلفة من خلال تقنيات متقدمة مثل تخزين الطاقة وتداول الطاقة بين الأفراد (P2P). ومع ذلك، لا تزال هناك تحديات متعددة، من بينها عدم اليقين التنظيمي، الحاجة إلى استثمارات رأسمالية مرتفعة، المشكلات التقنية المتعلقة بحماية الأنظمة وتكاملها، ومحدودية التوافق مع الأجهزة التي تعمل بالتيار المباشر. إن معالجة هذه التحديات من خلال إصلاحات السياسات، التقدم التكنولوجي، ومشاركة المجتمعات المحلية سيكون أمرًا حاسمًا لتحقيق الإمكانات الكاملة للشبكات المصغرة للطاقة المتجددة كأنظمة طاقة مستدامة في المستقبل. باختصار، تراوحت تكلفة الكهرباء المستوية لشبكات الطاقة الصغيرة المستقلة ذات الخدمة الأساسية بين 0.39 دولار أمريكي لكل كيلووات ساعة و0.58 دولار أمريكي/كيلووات ساعة، في حين أظهرت أنظمة الخدمة الكاملة المستقلة قيم تكلفة كهرباء مستوية تتراوح بين 0.50 دولار أمريكي/كيلووات ساعة و0.75 دولار أمريكي/كيلووات ساعة. وتوضح مقاييس التكلفة هذه أن شبكات الطاقة الصغيرة التي تعمل بالكامل بالطاقة المتجددة تمثل بديلاً تنافسيًا من حيث التكلفة لمولدات البنزين والديزل الصغيرة، والتي تتراوح تكلفة الكهرباء المستوية فيها عادةً من 0.35 دولار أمريكي/كيلووات ساعة إلى 0.70 دولار أمريكي/كيلووات ساعة.

الكلمات المفتاحية: الطاقة المتجددة، الشبكات المصغرة، البنية التحتية للجودة، التيار المباشر منخفض الجهد.

Introduction

Renewable mini-grids offer a significant opportunity to reduce greenhouse gas (GHG) emissions and contribute to low-emission development pathways by replacing or complementing fossil fuel-based energy systems [1-3]. Their integration into energy systems, particularly in off-grid and rural settings, enables the deployment of clean, decentralized power generation, which not only improves energy access but also mitigates the environmental impacts associated with conventional diesel or gasoline generators. Mini-grids powered by renewable sources—such as solar photovoltaic (PV), wind, hydropower, and bioenergy—produce electricity without direct carbon emissions, making them essential in global decarbonization strategies [4-7].

The expansion of mini-grid markets necessitates the development of a robust quality infrastructure to guarantee that deployed systems consistently provide the anticipated services and long-term benefits. Establishing comprehensive international standards, along with reliable testing and certification facilities, is essential to maintaining the high-performance standards of renewable mini-grid deployments [8-12]. The critical operational components of a renewable mini-grid encompass power generation, energy storage, energy conversion, consumption, and the integrated functions of control, management, and measurement (CMM). In this context, the renewable mini-grids of the future will exhibit significantly enhanced control, management, and measurement (CMM) capabilities, driven by advancements in smart metering systems, the proliferation of Internet of Things (IoT) technologies, and the availability of real-time data and predictive analytics for renewable energy generation. These developments will enable more precise monitoring, efficient energy allocation, and dynamic system optimization, ultimately fostering greater reliability and performance in mini-grid operations [13-17].

Future mini-grids will be characterized by their inherent intelligence, leveraging comprehensive data collection and IoT-based platforms as the central framework for CMM functionality. IoT systems will interconnect various components, such as energy generation units, storage systems, and consumption devices, creating a fully integrated and self-regulating energy ecosystem [18-23]. These platforms will allow for real-time communication between devices, enabling dynamic load management, predictive maintenance, fault detection, and energy optimization through advanced algorithms and machine learning models. Additionally, improved forecasting techniques for renewable energy generation—based on historical weather patterns, real-time meteorological data, and AI-driven models—will further enhance system resilience by ensuring better planning for supply-demand fluctuations [24-29].

Moreover, innovative transaction technologies, including blockchain-based platforms, will enable secure and transparent peer-to-peer (P2P) electricity trading within mini-grid communities. As depicted in Figure 1, mini-grids provide an ideal environment for P2P trading, where prosumers can sell excess electricity directly to other users, thus maximizing the utilization of locally generated renewable energy and reducing dependency on external power sources. P2P trading mechanisms will be governed by smart contracts, ensuring automated transactions and equitable energy distribution based on demand and supply conditions [30-32].

The evolution of storage technologies will play a pivotal role in shaping the future of mini-grids, offering diverse solutions tailored to various applications. Advanced battery systems, including lithium-ion, solid-state, and emerging technologies such as sodium-ion and flow batteries, will provide efficient short-term energy storage with improved cycle life and energy density [33-40]. Electrolyzer-based hydrogen storage systems will complement battery storage by offering long-duration storage options, especially in regions with surplus renewable energy [41-49]. Such innovations will enable mini-grids to operate efficiently even under prolonged periods of low renewable energy generation, ensuring continuity of power supply.

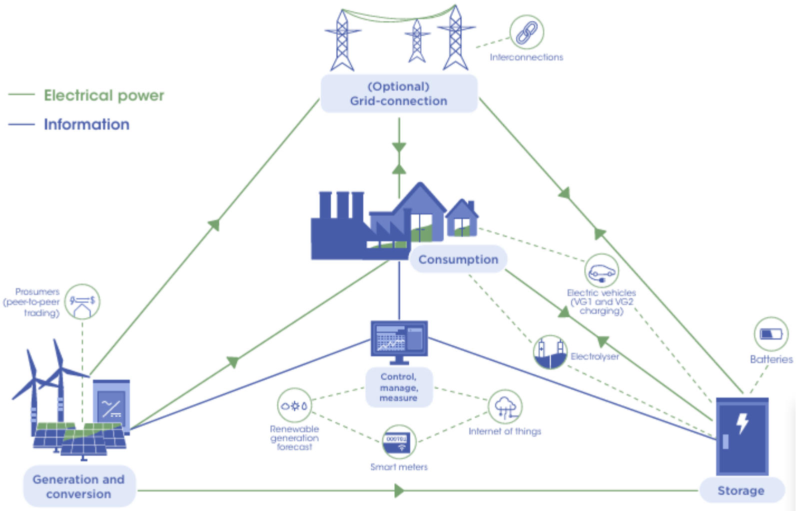

Figure 1. The Next Generation Renewable Mini-Grids.

Moreover, hybrid storage configurations, which combine different storage technologies, will optimize performance by balancing short-term and long-term energy needs. These configurations will address issues such as peak shaving, load shifting, and frequency regulation, making mini-grids more adaptable to fluctuating demand and intermittent renewable inputs [50-61].
The integration of electric vehicles into mini-grid systems presents both opportunities and challenges distinct from those encountered in national grid infrastructure. EVs, functioning as mobile energy storage units, can store excess renewable power during periods of low demand and discharge it back into the grid when needed, thereby enhancing grid stability and improving overall energy utilization. Vehicle-to-grid (V2G) and vehicle-to-home (V2H) technologies will be integral to this process, allowing bidirectional energy flow and seamless integration [62-64].
However, the decentralized nature of mini-grids introduces unique challenges, such as the need for localized load management, real-time control of charging/discharging cycles, and mitigation of potential overloads. Unlike centralized grids, mini-grids require more granular coordination to balance the intermittent nature of renewable energy with the variable charging needs of EVs. This will necessitate the deployment of sophisticated energy management systems that can prioritize energy distribution based on real-time conditions [64-67].
On the demand side, the traditional role of consumers will evolve into that of prosumers—individuals or entities capable of generating, storing, and consuming their own electricity while contributing surplus power to the grid. This transition is being accelerated by technological advancements in localized generation (e.g., rooftop solar PV), energy storage, and control systems. Distributed energy resources (DERs) will empower prosumers to actively participate in energy markets and optimize their energy consumption patterns.

Current State of Renewable Mini-Grids

Significant efforts have been made to gather comprehensive data on mini-grid systems, yet discrepancies persist across various sources due to the sector's rapid evolution in recent years. Estimating the global distribution of mini-grids—whether grid-connected or off-grid—powered by renewable energy sources remains a challenge due to the dynamic nature of the industry [68-71]. However, more consistent data exists regarding the total number of mini-grids worldwide. According to the Energy Sector Management Assistance Program (ESMAP, 2019), approximately 19,000 mini-grids have been installed globally, with nearly half relying on diesel or other fossil fuel-based generators. This presents a significant opportunity to transition a substantial portion of carbon-emitting mini-grids to renewable energy-powered alternatives.

- Global Capacity and Market Potential

The International Renewable Energy Agency (IRENA) estimates that the global installed capacity of off-grid renewable energy mini-grids stands at 4.16 gigawatts (GW), serving at least 8 million people. As illustrated in Figure 2, this capacity is distributed across a variety of energy sources, each catering to specific end-use sectors and applications. Among them, bioenergy-based mini-grids exhibit the highest installed capacity, primarily due to their deployment in high-power industrial applications, where bioenergy can meet large-scale, continuous energy demands [71-77].

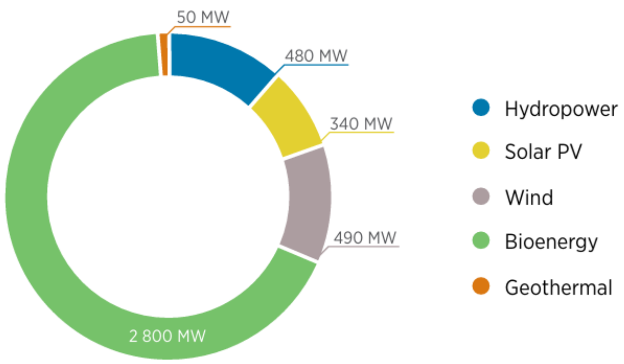

Figure 2: Overall power generation for autonomous (off-grid) mini-grids (megawatts).

The total capacity of autonomous (off-grid) mini-grids highlights the dominant role of bioenergy, accounting for 2,800 MW, with significant contributions from hydropower (480 MW), wind (490 MW), and solar PV (340 MW). Geothermal remains a smaller contributor at 50 MW, reflecting its limited deployment in off-grid systems. This distribution indicates that bioenergy-based mini-grids, often utilized in high-demand industrial applications, currently lead the market due to their capacity for continuous power generation. However, the significant shares of hydropower, wind, and solar PV underscore the growing diversification of renewable sources in mini-grids. Moving forward, strategic investment in technologies like solar PV and wind, supported by advances in energy storage and system integration, will be essential for optimizing off-grid mini-grids and enhancing energy access in remote areas.

- Solar Photovoltaic (PV) Mini-Grids

Solar PV mini-grids have gained prominence, particularly in commercial, residential, and agricultural sectors. Their modular design, ease of installation, and decreasing costs have made them an attractive solution for off-grid electrification and decentralized energy supply. In rural and remote areas, solar PV mini-grids often support agricultural activities such as irrigation, crop drying, and storage, thereby contributing to socioeconomic development.

- Wind and Hydropower Mini-Grids

Mini-grids powered by wind and hydropower are deployed across diverse end-use sectors, reflecting their versatility in both small-scale and large-scale applications. Hydropower-based mini-grids, in particular, have experienced notable growth in recent years, expanding into residential and industrial sectors due to their reliability and cost-effectiveness in regions with abundant water resources.

- Bioenergy-Based Mini-Grids

Bioenergy mini-grids dominate the installed capacity landscape, particularly in industrial applications where their ability to provide consistent power output is highly valued. The availability of agricultural and industrial biomass feedstocks further supports their widespread adoption in energy-intensive industries.

- Hydrogen (H2) Mini-Grids

Hydrogen is poised to play a transformative role in future renewable mini-grids, offering long-duration energy storage, decarbonization, and multi-sector integration. Produced through renewable-powered electrolysis or biomass gasification, hydrogen can store excess renewable energy for later use, addressing the intermittency of solar and wind sources. It enables seasonal storage, with fuel cells converting stored hydrogen into electricity when needed, while also supporting combined heat and power (CHP) and hydrogen-fueled transport within mini-grid systems. Although challenges remain, such as efficiency losses, storage limitations, and infrastructure development, ongoing advancements in electrolyzer efficiency, hybrid storage solutions, and localized production technologies are making hydrogen-driven mini-grids increasingly viable. As costs decline, hydrogen-based hybrid mini-grids are expected to deliver reliable, resilient, and sustainable energy for off-grid and remote areas.
It is worthy to mention that, the market potential for replacing fossil fuel-powered mini-grids with renewable alternatives is substantial, offering environmental, economic, and social benefits. As technology costs decline and innovative financing mechanisms emerge, the deployment of renewable mini-grids is expected to accelerate, supporting global efforts to transition towards clean and

sustainable energy systems. With further advancements in energy storage, control systems, and integration technologies, renewable mini-grids will play a pivotal role in achieving energy access, climate resilience, and rural development objectives on a global scale.
In recent years, the overall cost of mini-grid hardware has experienced a significant decline, primarily driven by heightened market competition and policy-driven incentives. However, the reduction of soft costs—encompassing customized engineering studies, regulatory compliance, environmental assessments, and interconnection requirements—has been comparatively slower due to non-competitive regulatory constraints and administrative inefficiencies. As a result, these soft costs now constitute a larger proportion of the total mini-grid deployment expenses compared to previous years.. In 2020, the levelized cost of electricity (LCOE) for autonomous basic service mini-grids ranged between USD 0.39 per kilowatt-hour (kWh) and USD 0.58/kWh, while autonomous full-service systems exhibited LCOE values ranging from USD 0.50/kWh to USD 0.75/kWh. These cost metrics demonstrate that mini-grids powered entirely by renewable energy represent a cost-competitive alternative to small gasoline and diesel generators, whose LCOE typically ranges from USD 0.35/kWh to USD 0.70/kWh.

Quality Infrastructure: A Critical Driver for Sustainable Mini-Grid Development
The sustainable growth and long-term profitability of renewable mini-grids are fundamentally dependent on the establishment of a robust quality infrastructure (QI) as illustrated in Figure 3. Given the complexity of mini-grid systems—comprising multiple suppliers, diverse applications, and high regulatory uncertainty surrounding their installation and operation—QI plays a pivotal role in mitigating risks and ensuring reliable performance [78-83].

Figure 3: QI Aspects.

The primary components of QI for mini-grids include comprehensive standards, testing, certification and accreditation, inspection and monitoring, and metrology, all of which collectively contribute to reducing system failures and fostering market trust. While QI serves as a primary driver for promoting stable mini-grid deployment, its influence is particularly pronounced in areas with significant regulatory challenges and technical variability. Comprehensive standards ensure that systems meet predefined technical and safety requirements, fostering compatibility across components and minimizing operational disruptions. Testing and certification further validate compliance with these standards, enhancing system reliability and promoting investor confidence. Meanwhile, inspection and monitoring mechanisms provide ongoing oversight of system performance, enabling timely maintenance and early fault detection. Metrology ensures accurate measurement of critical parameters, which is essential for energy accounting, efficiency monitoring, and load management.

Emerging Trends: Low-Voltage Direct Current (LVDC) Mini-Grids
The inherent characteristics of renewable mini-grids—such as DC-based power generation, limited system size, and tailored user profiles—are paving the way for innovative energy distribution methods aimed at enhancing efficiency and cost-effectiveness. One of the most promising developments is the deployment of low-voltage direct current (LVDC) mini-grids and DC-compatible appliances, which offer significant advantages over traditional AC systems [84-88].

- Advantages of LVDC Distribution in Renewable Mini-Grids

LVDC mini-grids present several benefits, particularly when integrated with distributed renewable energy resources (DERs), due to reduced power conversion losses and simplified system configurations. Compared to conventional AC systems, LVDC grids feature improved:

  - Energy and Cost Efficiency:

LVDC systems minimize energy losses by reducing the number of conversion steps (e.g., DC-AC and AC-DC), eliminating the need for inverters that typically operate under part-load conditions and reduce system efficiency.

- Reliability and Power Quality:

DC systems provide stable and continuous power without the frequency fluctuations inherent to AC systems, making them suitable for applications requiring high-quality power, such as data centers and sensitive electronics.

- Expandability and Scalability:

LVDC grids are more easily scalable and can accommodate additional distributed energy resources and load demands without requiring significant modifications.

- Applications of LVDC Mini-Grids

LVDC distribution is gaining traction in various settings, such as data centers, commercial buildings, and increasingly in rural, off-grid, or island mini-grid systems powered by renewables. They are particularly beneficial for regions where renewable DERs like solar PV and wind turbines form the backbone of the power supply, as these sources naturally generate DC power. Eliminating the need for AC inverters results in more efficient power delivery and cost savings over time.

- Challenges and Technical Considerations

Despite its advantages, the adoption of LVDC mini-grids faces several challenges, particularly related to technical standards, protection mechanisms, and the limited availability of compatible appliances:

- Grounding, Bonding, and Earthing:

There is still a lack of standardized design guidelines for grounding and bonding in DC systems, creating risks in terms of safety and operational reliability.

- Protection and Safety

One of the major challenges of DC systems is the absence of zero-crossing currents, which makes fault interruption more difficult compared to AC systems. Conventional fuses and circuit breakers are less effective in DC environments due to prolonged arcing and higher fault-clearing times. Advanced protection technologies, such as DC-specific circuit breakers and fault detection systems, are under development but require further refinement for widespread adoption.

- Compatibility with Appliances

The most significant drawback of LVDC systems is their limited compatibility with conventional appliances, which are primarily designed for AC grids. Although the market for DC-compatible appliances is expanding, further development is needed to fully bridge this gap. Many modern appliances, such as LED lighting, mobile devices, TVs, computers, and brushless DC motors, operate more efficiently on DC power or require AC-DC converters, highlighting the potential for wider adoption. For example, productive-use applications (e.g., DC-powered irrigation systems and refrigerators) and non-productive uses (e.g., M-Kopa solar TVs and SunDanzer DC refrigerators) are emerging as key markets.

- The Diminishing Advantages of AC Distribution

Historically, AC distribution dominated electricity grids due to its compatibility with transformers, which facilitated the easy transmission of power over long distances by adjusting voltage levels. However, advancements in power electronics and the increasing deployment of localized renewable energy systems are diminishing the traditional advantages of AC grids. In this direction, modern power electronics enable effective voltage regulation, conversion, and load management within LVDC grids, making them viable competitors to AC-based systems, especially in localized energy networks.

Thus, the deployment of LVDC mini-grids is expected to grow as renewable DERs become more widespread and technological challenges related to protection, safety, and appliance compatibility are further addressed. Continued development of quality infrastructure (QI)—including standards for DC grounding, fault detection, and metrology—will be critical for scaling LVDC systems. With improvements in power electronics and the expanding market for DC appliances, LVDC mini-grids are poised to play a key role in future decentralized energy systems, offering enhanced efficiency, reliability, and sustainability.

Opportunities for Renewable Mini-Grids of the Future

The future of renewable mini-grids presents significant opportunities to transform energy systems, particularly in remote, off-grid, and underserved regions. As renewable energy technologies evolve and decentralized energy systems gain traction, the following key opportunities emerge:

- Expansion of Energy Access in Remote and Underserved Areas

Renewable mini-grids offer a cost-effective and scalable solution to extend electricity access to rural or off-grid communities where extending the central grid is economically unfeasible. By integrating solar

PV, wind, bioenergy, and small hydropower, mini-grids can provide reliable and sustainable electricity, thereby promoting rural development, improving living standards, and enhancing local economic activities.

- Enhanced Energy Security and Resilience

Renewable mini-grids reduce dependence on centralized power systems and fossil fuel imports by leveraging locally available renewable resources. This decentralized approach ensures continuous power supply, even during disruptions to the main grid, thereby improving energy resilience and security, particularly in disaster-prone or climate-vulnerable regions.

- Decarbonization and Climate Mitigation

The replacement of diesel-based mini-grids with renewable energy-based systems represents a critical opportunity to reduce greenhouse gas emissions and air pollution. The deployment of 100% renewable mini-grids supports national and global carbon reduction targets, aligning with international climate agreements and sustainability goals.

- Technological Advancements in Energy Storage and Control

Innovations in energy storage technologies—such as lithium-ion, flow batteries, and hydrogen storage—allow for better integration of intermittent renewable sources and ensure reliable power delivery. Advanced control systems, powered by artificial intelligence (AI) and the Internet of Things (IoT), enable real-time energy management, load optimization, and predictive maintenance, further enhancing operational efficiency.

- Emergence of Low-Voltage Direct Current (LVDC) Mini-Grids

LVDC distribution systems provide a more efficient alternative to traditional AC systems by reducing conversion losses, simplifying system design, and supporting the direct integration of DC-based renewable sources and appliances. As DC-compatible appliances become more widespread, LVDC mini-grids offer significant opportunities for improved energy efficiency and cost savings.

- Integration of Electric Vehicles (EVs) as Mobile Storage Units

The integration of EVs within mini-grid systems presents a dual opportunity for energy storage and demand-side flexibility. EVs can store surplus renewable energy and discharge it back into the grid when needed, thereby stabilizing power supply and optimizing system performance.

- Peer-to-Peer Energy Trading and Prosumers

Future renewable mini-grids will support the growth of prosumers (users who both produce and consume energy) and enable peer-to-peer (P2P) energy trading within local communities through blockchain-based platforms and smart contracts. This decentralized market structure maximizes the use of locally generated renewable energy, promotes economic participation, and incentivizes further investments in small-scale generation.

- Productive Use Applications for Socioeconomic Development

Renewable mini-grids can power productive activities, such as irrigation, agro-processing, refrigeration, and small-scale manufacturing, fostering local enterprise development and job creation. By enabling productive uses of electricity, mini-grids contribute to economic growth and poverty alleviation in rural areas.

- Hybrid Mini-Grids with Sector Coupling

Future mini-grids are expected to integrate power, heating, and transportation sectors through sector coupling, enhancing overall energy efficiency. For instance, excess electricity can be used for hydrogen production (via electrolysis), which can be stored or used for transport and industrial applications, creating a circular energy system.

- Green Financing and Policy Incentives

The increasing availability of green financing mechanisms, such as climate funds and carbon credits, presents an opportunity to accelerate the deployment of renewable mini-grids. Supportive policies, including subsidies, tax incentives, and streamlined permitting processes, further enhance their economic feasibility and attract private sector investment.

Renewable mini-grids of the future are set to revolutionize energy access and sustainability by leveraging technological innovation, decentralized models, and renewable resources. As the costs of key technologies continue to decline and regulatory frameworks improve, these systems will play a pivotal role in achieving universal energy access, decarbonization, and resilient energy infrastructures globally.

Challenges for Renewable Mini-Grids of the Future

As renewable mini-grids continue to expand globally, their integration with national and regional grids has become a critical factor in achieving sustainable energy systems. Mini-grids, initially designed for isolated or off-grid operation, are increasingly being connected to larger grids to enhance energy reliability, optimize resource sharing, and support national electrification goals. However, this integration presents several technical, operational, and regulatory challenges. The interoperability between mini-grids and centralized grids involves complex issues such as synchronization, voltage stability, frequency control, and bidirectional power flow management. Without proper mechanisms, integration could lead to power quality disruptions, system inefficiencies, and curtailment of renewable generation. Addressing these challenges requires advanced technologies, grid codes, and regulatory frameworks to ensure that mini-grids seamlessly interact with centralized systems while maximizing their contributions to grid stability and renewable energy penetration.

- Technical Integration of Intermittent Renewable Energy Sources

Intermittency remains a major challenge in renewable mini-grids, as solar and wind power generation depends on weather conditions and time of day. Without adequate storage and balancing mechanisms, power fluctuations and outages can occur, limiting reliability and end-user satisfaction. To mitigate this challenge, mini-grids must adopt hybrid systems that combine multiple renewable sources, such as solar, wind, and bioenergy, to provide a more stable power supply. In addition, advancements in energy storage technologies and smart load management systems, such as AI-driven grid balancing, are essential to ensure continuous and reliable power delivery.

- High Initial Capital Investment

One of the primary challenges facing renewable mini-grids is the high initial capital investment required for system deployment. The costs associated with procuring and installing solar PV panels, wind turbines, battery storage, and grid infrastructure can be prohibitively expensive for low-income communities and developing regions. This financial barrier limits the ability of mini-grids to scale and deters private sector involvement, as investors often seek quicker returns. Addressing this challenge requires expanding access to concessional financing, leveraging public-private partnerships, and implementing green financing mechanisms such as climate funds and grants. As technology costs continue to decline, the right financial support structures can help accelerate deployment and overcome this barrier.

- Regulatory and Policy Uncertainty

The absence of clear and supportive regulatory frameworks presents a major obstacle to the deployment of renewable mini-grids. Uncertainty regarding licensing procedures, tariffs, environmental compliance, and grid interconnection policies creates financial risks for developers and delays project implementation. Without well-defined regulations, mini-grid operators face difficulties in securing long-term revenue streams and investment. Governments must establish comprehensive regulatory frameworks that streamline licensing, enable tariff flexibility, and incentivize grid integration. Providing legal clarity will attract investment and facilitate sustainable growth in the sector.

- Limited Energy Storage and Cost Constraints

Although battery technology has witnessed significant advancements, the cost and capacity of energy storage systems remain a critical barrier to the scalability of renewable mini-grids. Batteries are often expensive, especially for long-duration or seasonal storage, making it difficult to maintain continuous power supply during prolonged periods of low renewable generation. Diversifying storage options by incorporating emerging technologies, such as hydrogen storage and flow batteries, can address this limitation. Continued investment in R&D and economies of scale will further reduce storage costs and improve the feasibility of long-term renewable mini-grids.

- Protection, Safety, and Technical Reliability Issues

Technical challenges related to protection, grounding, and system safety hinder the widespread adoption of renewable mini-grids, particularly those utilizing low-voltage direct current (LVDC) systems. In DC grids, the absence of zero-crossing currents makes fault isolation and protection more complex, as conventional circuit breakers and fuses are less effective. Additionally, DC systems face issues with arcing and prolonged fault-clearing times, which can compromise safety. The development of advanced DC-specific protection mechanisms, such as fast-acting circuit breakers and arc suppression devices, along with standardized safety guidelines, is essential to overcoming these reliability challenges.

- Limited Availability of DC-Compatible Appliances

The widespread use of AC-based appliances poses a challenge for LVDC mini-grids, as most household and industrial devices are not designed to operate on DC power. Although many modern devices, such as LED lights, computers, and mobile chargers, internally convert AC to DC, the lack of dedicated DC-compatible appliances reduces overall system efficiency by introducing conversion losses. Expanding the market for DC-compatible appliances, particularly for productive use applications like agricultural machinery, refrigerators, and water pumps, can significantly enhance the efficiency of LVDC mini-grids. Incentivizing manufacturers and developing quality standards for DC appliances will further bridge this gap.

- Challenges in Grid Integration and Interoperability

In many cases, mini-grids are designed to operate in isolation, making their future integration with national or regional grids technically challenging. Interoperability issues related to synchronization, power quality, and bidirectional energy flow must be resolved to ensure a smooth transition when connecting mini-grids to larger grid infrastructures. Without proper integration, excess renewable energy may be curtailed, and operational inefficiencies may arise. Advanced power electronics, grid-forming inverters, and smart controllers are critical to addressing these challenges and enabling seamless energy exchange between mini-grids and national grids.

- Maintenance, Operations, and Skills Gaps

In many rural areas, the lack of skilled personnel to maintain and operate renewable mini-grids poses a significant operational challenge. Inadequate maintenance can lead to frequent system failures, reduced lifespan of components, and increased costs. Establishing training programs for local technicians and operators is essential to address this issue. Remote monitoring systems powered by IoT and AI can provide predictive maintenance capabilities, enabling timely identification of issues before they escalate. Modular system designs that allow for easy maintenance and part replacement will also reduce operational challenges.

All in All, Addressing the challenges associated with renewable mini-grids is crucial to ensuring their long-term viability and scalability. Collaborative efforts between governments, private investors, and local communities, combined with targeted technological advancements and policy reforms, are necessary to overcome these obstacles. With the right support, renewable mini-grids can play a transformative role in global energy access and decarbonization.

Conclusion

Renewable mini-grids are positioned to play a transformative role in the future of global energy systems by offering decentralized, sustainable, and resilient energy solutions. However, their successful deployment depends on overcoming a range of challenges and leveraging emerging opportunities. The development of robust quality infrastructure is essential to ensure reliable performance and reduce risks associated with the complexity of mini-grid systems. Emerging trends, particularly the adoption of low-voltage direct current (LVDC) mini-grids, present a promising avenue for improving energy efficiency, power quality, and system expandability. With expanding markets for renewable energy technologies, mini-grids can facilitate broader energy access, power economic development, and support global decarbonization targets. Nonetheless, challenges such as high capital costs, regulatory uncertainty, and technical integration issues must be addressed through coordinated efforts involving policymakers, technology providers, and financial institutions. By fostering technological innovation, enabling regulatory clarity, and ensuring stakeholder collaboration, renewable mini-grids can evolve into key drivers of a sustainable, inclusive, and low-carbon future.

Reference

[1] E. I. Come Zebra, H. J. van der Windt, G. Nhumaio, and A. P. C. Faaij, “A review of hybrid renewable energy systems in mini-grids for off-grid electrification in developing countries,” *Renew. Sustain. Energy Rev.*, vol. 144, no. 111036, p. 111036, 2021.

[2] J. Peters, M. Sievert, and M. A. Toman, “Rural electrification through mini-grids: Challenges ahead,” *Energy Policy*, vol. 132, pp. 27–31, 2019.

[3] M. Khaleel *et al.*, “Evolution of emissions: The role of clean energy in sustainable development,” *Chall. Sustain.*, vol. 12, no. 2, pp. 122–135, 2024.

[4] S. C. Bhattacharyya, D. Palit, G. K. Sarangi, V. Srivastava, and P. Sharma, “Solar PV mini-grids versus large-scale embedded PV generation: A case study of Uttar Pradesh (India),” *Energy Policy*, vol. 128, pp. 36–44, 2019.

[5] O. O. Babayomi *et al.*, “A review of renewable off-grid mini-grids in Sub-Saharan Africa,” *Front. Energy Res.*, vol. 10, 2023.

[6] M. Khaleel *et al.*, “Emerging issues and challenges in integrating of solar and wind,” *Int. J. Electr. Eng. and Sustain.*, pp. 1–11, 2024.

[7] Y. F. Nassar *et al.*, “Assessing the viability of solar and wind energy technologies in semi-arid and arid regions: A case study of Libya’s climatic conditions,” *Appl. Sol. Energy*, vol. 60, no. 1, pp. 149–170, 2024.

[8] A. Alsharif, E. Almabsout, A. A. Ahmed, M. Khaleel, Y. F. Nassar, and H. J. El-Khozoadar, “Optimal sizing of hybrid renewable system for residential appliances,” in *2024 IEEE 4th International Maghreb Meeting of the Conference on Sciences and Techniques of Automatic Control and Computer Engineering (MI-STA)*, 2024.

[9] J. Yan, Y. Zhai, P. Wijayatunga, A. M. Mohamed, and P. E. Campana, “Renewable energy integration with mini/micro-grids,” *Appl. Energy*, vol. 201, pp. 241–244, 2017.

[10] A. S. Duran and F. G. Sahinyazan, “An analysis of renewable mini-grid projects for rural electrification,” *Socioecon. Plann. Sci.*, vol. 77, no. 100999, p. 100999, 2021.

[11] A. Korkovelos, H. Zerriffi, M. Howells, M. Bazilian, H.-H. Rogner, and F. Fuso Nerini, “A retrospective analysis of energy access with a focus on the role of mini-grids,” *Sustainability*, vol. 12, no. 5, p. 1793, 2020.

[12] A. Ahmed *et al.*, “Strategic renewable energy source integration for charging stations in plugin hybrid electric vehicle networks,” in *Proceedings of the EAI 3rd International Conference on Intelligent Systems and Machine Learning, ICISML 2024, January 5-6, 2024, Pune, India*, 2024.

[13] M. Khaleel *et al.*, “An optimization approaches and control strategies of hydrogen fuel cell systems in EDG-integration based on DVR technology,” *J. Eur. Syst. Autom.*, vol. 57, no. 2, pp. 551–565, 2024.

[14] M. Moner-Girona, M. Solano-Peralta, M. Lazopoulou, E. K. Ackom, X. Vallve, and S. Szabó, “Electrification of Sub-Saharan Africa through PV/hybrid mini-grids: Reducing the gap between current business models and on-site experience,” *Renew. Sustain. Energy Rev.*, vol. 91, pp. 1148–1161, 2018.

[15] D. Suri, “Site selection framework for mini-grids in developing countries: An overview,” *Electr. J.*, vol. 33, no. 7, p. 106803, 2020.

[16] S. Abulifa, M. Elbar, M. Mohamed, A. Khoudiri, and S. Khoudiri, “Performance evaluation of MG systems interfaced with wind turbines employing DFIG technology,” *INT. J. ELECTR. ENG. AND SUSTAIN.*, vol. 2, no. 2, pp. 22–35, 2024.

[17] A. Gill-Wiehl, S. Miles, J. Wu, and D. M. Kammen, “Beyond customer acquisition: A comprehensive review of community participation in mini grid projects,” *Renew. Sustain. Energy Rev.*, vol. 153, no. 111778, p. 111778, 2022.

[18] A. Pueyo and S. DeMartino, “The impact of solar mini-grids on Kenya’s rural enterprises,” *Energy Sustain. Dev.*, vol. 45, pp. 28–37, 2018.

[19] I. Abada, M. Othmani, and L. Tatry, “An innovative approach for the optimal sizing of mini-grids in rural areas integrating the demand, the supply, and the grid,” *Renew. Sustain. Energy Rev.*, vol. 146, no. 111117, p. 111117, 2021.

[20] W. Commerell, “The grid of the future,” in *Sustainable Energy Solutions for Remote Areas in the Tropics*, Cham: Springer International Publishing, 2020, pp. 239–269.

[21] B. Poudel, K. Parton, and M. Morrison, “The drivers of the sustainable performance of renewable energy-based mini-grids,” *Renew. Energy*, vol. 189, pp. 1206–1217, 2022.

[22] F. Antonanzas-Torres, J. Antonanzas, and J. Blanco-Fernandez, “State-of-the-art of mini grids for rural electrification in West Africa,” *Energies*, vol. 14, no. 4, p. 990, 2021.

[23] M. Khaleel, Z. Yusupov, A. Ahmed, A. Alsharif, Y. Nassar, and H. El-Khozondar, “Towards sustainable renewable energy,” *Appl. Sol. Energy*, vol. 59, no. 4, pp. 557–567, 2023.

[24] A. O. Cyril, C. O. Ujah, B. N. Ekwueme, and C. O. Asadu, “Photovoltaic mini-grid incorporation: The panacea for electricity crisis in sub-Saharan Africa,” *Unconventional Resources*, vol. 4, no. 100079, p. 100079, 2024.

[25] C. Pirie *et al.*, “A survey of AI-powered mini-grid solutions for a sustainable future in rural communities,” *arXiv [cs.LG]*, 2024.

[26] V. Mwale, R. Blanchard, T. Ngonda, R. Nkhoma, C. Ogunna, and L. S. To, “The quest for resilient sustainable development and low-carbon energy transitions: Investigating the challenges and success factors for mini-grids in Malawi,” *Sustainability*, vol. 16, no. 12, p. 5060, 2024.

[27] “View of intelligent control techniques for microgrid systems,” *Itscience.org*. [Online]. Available: https://jurnal.itscience.org/index.php/brilliance/article/view/2192/1648. [Accessed: 01-Feb-2025].

[28] M. Khaleel, “Intelligent Control Techniques for Microgrid Systems,” *Brilliance*, vol. 3, no. 1, pp. 56–67, 2023.

[29] M. Moner-Girona *et al.*, “Adaptation of Feed-in Tariff for remote mini-grids: Tanzania as an illustrative case,” *Renew. Sustain. Energy Rev.*, vol. 53, pp. 306–318, 2016.

[30] J. Abdella and K. Shuaib, “Peer to peer distributed energy trading in smart grids: A survey,” *Energies*, vol. 11, no. 6, p. 1560, 2018.

[31] A. Aoun, M. Adda, A. Ilinca, M. Ghandour, and H. Ibrahim, “Comparison between blockchain P2P energy trading and conventional incentive mechanisms for distributed energy resources—A rural microgrid use case study,” *Appl. Sci. (Basel)*, vol. 14, no. 17, p. 7618, 2024.

[32] M. H. Ullah and J.-D. Park, "A two-tier distributed market clearing scheme for peer-to-peer energy sharing in smart grid," *IEEE Trans. Industr. Inform.*, vol. 18, no. 1, pp. 66–76, 2022.

[33] M. Khaleel, Z. Yusupov, M. Guneser, H. El-Khozondar, A. Ahmed, and A. A. Alsharif, "Towards hydrogen sector investments for achieving sustainable electricity generation," *jsesd*, vol. 13, no. 1, pp. 71–96, 2024.

[34] Y. F. Nassar *et al.*, "Thermoelectrical analysis of a new hybrid PV-thermal flat plate solar collector," in *2023 8th International Engineering Conference on Renewable Energy & Sustainability (ieCRES)*, 2023.

[35] M. Khaleel, Z. Yusupov, M. Elmnifi, T. Elmenfy, Z. Rajab, and M. Elbar, "Assessing the financial impact and mitigation methods for voltage sag in power grid," *Int. J. Electr. Eng. and Sustain.*, pp. 10–26, 2023.

[36] K. Nyarko, T. Urmee, J. Whale, Y. Simsek, and Y. Haigh, "Assessing the effectiveness of energy policies in accelerating renewable energy-based mini-grid deployment: A case study," *Energy Sustain. Dev.*, vol. 85, no. 101631, p. 101631, 2025.

[37] E. Guillou and B. Girard, "Mini-grids at the interface: The deployment of mini-grids in urbanizing localities of the global south," *J. Urban Technol.*, pp. 1–20, 2022.

[38] E. Boyko, F. Byk, P. Ilyushin, L. Myshkina, and K. Suslov, "Methods to improve reliability and operational flexibility by integrating hybrid community mini-grids into power systems," *Energy Rep.*, vol. 9, pp. 481–494, 2023.

[39] L. Lorenzoni, P. Cherubini, D. Fioriti, D. Poli, A. Micangeli, and R. Giglioli, "Classification and modeling of load profiles of isolated mini-grids in developing countries: A data-driven approach," *Energy Sustain. Dev.*, vol. 59, pp. 208–225, 2020.

[40] M. Khaleel *et al.*, "The impact of SMES integration on the power grid: Current topologies and nonlinear control strategies," in *New Technologies, Development and Application VII*, Cham: Springer Nature Switzerland, 2024, pp. 108–121.

[41] R. Tatti, M. Petrollese, M. Lucariello, F. Serra, and G. Cau, "Hydrogen storage integrated in off-grid power systems: a case study," *Int. J. Hydrogen Energy*, vol. 79, pp. 164–176, 2024.

[42] N. Thakkar and P. Paliwal, "Hydrogen storage based micro-grid: A comprehensive review on technology, energy management and planning techniques," *Int. J. Green Energy*, pp. 1–19, 2022.

[43] P. Marocco, D. Ferrero, A. Lanzini, and M. Santarelli, "Optimal design of stand-alone solutions based on RES + hydrogen storage feeding off-grid communities," *Energy Convers. Manag.*, vol. 238, no. 114147, p. 114147, 2021.

[44] M. M. Khaleel, M. R. Adzman, and S. M. Zali, "An integrated of hydrogen fuel cell to distribution network system: Challenging and opportunity for D-STATCOM," *Energies*, vol. 14, no. 21, p. 7073, 2021.

[45] H. Chamandoust, A. Hashemi, and S. Bahramara, "Energy management of a smart autonomous electrical grid with a hydrogen storage system," *Int. J. Hydrogen Energy*, vol. 46, no. 34, pp. 17608–17626, 2021.

[46] L. Zhang and J. Xiang, "The performance of a grid-tied microgrid with hydrogen storage and a hydrogen fuel cell stack," *Energy Convers. Manag.*, vol. 87, pp. 421–427, 2014.

[47] M. M. Khaleel, M. Rafi, S. M. Zali, M. M. Graisa, and A. A. Ahmed, "A review of fuel cell to distribution network interface using D-FACTS: Technical challenges and interconnection trends," *Int. J. Electr. Electron. Eng. Telecommun.*, pp. 319–332, 2021.

[48] P. Marocco, D. Ferrero, A. Lanzini, and M. Santarelli, "The role of hydrogen in the optimal design of off-grid hybrid renewable energy systems," *J. Energy Storage*, vol. 46, no. 103893, p. 103893, 2022.

[49] M. Khaleel, Z. Yusupov, N. Yasser, and H. Elkhozondar, "Enhancing Microgrid performance through hybrid energy storage system integration: ANFIS and GA approaches," *International Journal of Electrical Engineering and Sustainability (IJEES)*, vol. 1, no. 2, pp. 38–48, 2023.

[50] A. M. Adeyinka, O. C. Esan, A. O. Ijaola, and P. K. Farayibi, "Advancements in hybrid energy storage systems for enhancing renewable energy-to-grid integration," *Sustainable Energy res.*, vol. 11, no. 1, 2024.

[51] A. Emrani and A. Berrada, "Modeling and optimal capacity configuration of dry gravity energy storage integrated in off-grid hybrid PV/Wind/Biogas plant incorporating renewable power generation forecast," *J. Energy Storage*, vol. 97, no. 112698, p. 112698, 2024.

[52] M. H. Elkholy *et al.*, “Techno-economic configuration of a hybrid backup system within a microgrid considering vehicle-to-grid technology: A case study of a remote area,” *Energy Convers. Manag.*, vol. 301, no. 118032, p. 118032, 2024.

[53] G. Er, G. Soykan, and E. Canakoglu, “Stochastic optimal design of a rural microgrid with hybrid storage system including hydrogen and electric cars using vehicle-to-grid technology,” *J. Energy Storage*, vol. 75, no. 109747, p. 109747, 2024.

[54] Z. Abdin, N. Al Khafaf, and B. McGrath, “Feasibility of hydrogen hybrid energy systems for sustainable on- and off-grid integration: An Australian REZs case study,” *Int. J. Hydrogen Energy*, vol. 57, pp. 1197–1207, 2024.

[55] L. Zhang *et al.*, “Hybrid electrochemical energy storage systems: An overview for smart grid and electrified vehicle applications,” *Renew. Sustain. Energy Rev.*, vol. 139, no. 110581, p. 110581, 2021.

[56] F. Alasali, A. S. Saidi, N. El-Naily, O. Alsmadi, M. Khaleel, and I. Ghirani, “Assessment of the impact of a 10-MW grid-tied solar system on the Libyan grid in terms of the power-protection system stability,” *Clean Energy*, vol. 7, no. 2, pp. 389–407, 2023.

[57] Y. F. Nassar *et al.*, “Design of reliable standalone utility-scale pumped hydroelectric storage powered by PV/Wind hybrid renewable system,” *Energy Convers. Manag.*, vol. 322, no. 119173, p. 119173, 2024.

[58] Y. L. Teo and Y. Go Ii, “Techno-economic-environmental analysis of solar/hybrid/storage for vertical farming system: A case study, Malaysia,” *Renew. Energy Focus*, vol. 37, pp. 50–67, 2021.

[59] A. Bensalem, B. Toual, A. Kouzou, M. Elbar, M. Khaleel, and Z. Belboul, “A framework to quantify battery degradation in residential microgrid operate with maximum self-consumption based energy management system,” *STUDIES IN ENGINEERING AND EXACT SCIENCES*, vol. 5, no. 1, pp. 354–370, 2024.

[60] O. S. M. Jomah, N. Mohamed, A. A. Ahmed, A. Alsharif, M. M. Khaleel, and Y. F. Nassar, “Simulating photovoltaic emulator systems for renewable energy analysis,” in *2024 IEEE 4th International Maghreb Meeting of the Conference on Sciences and Techniques of Automatic Control and Computer Engineering (MI-STA)*, 2024.

[61] A. M. Makhzom *et al.*, “Carbon dioxide Life Cycle Assessment of the energy industry sector in Libya: A case study,” *International Journal of Electrical Engineering and Sustainability (IJEES)*, vol. 1, no. 3, pp. 145–163, 2023.

[62] G. Mensah, R. Opoku, F. Davis, and G. Y. Obeng, “Techno-economic analysis of green hydrogen production and electric vehicle charging using redundant energy on a solar photovoltaic mini-grid,” *Cleaner Energy Systems*, vol. 9, no. 100165, p. 100165, 2024.

[63] A. Saffar and A. Ghasemi, “Energy management of a renewable-based isolated micro-grid by optimal utilization of dump loads and plug-in electric vehicles,” *J. Energy Storage*, vol. 39, no. 102643, p. 102643, 2021.

[64] C. L. Azimoh, P. Klintenberg, F. Wallin, B. Karlsson, and C. Mbohwa, “Electricity for development: Mini-grid solution for rural electrification in South Africa,” *Energy Convers. Manag.*, vol. 110, pp. 268–277, 2016.

[65] A. Abodwair, M. Guneser, M. Khaleel, Y. Nassar, H. El-Khozondar, and A. Elbaz, “Feasibility assessment of hybrid renewable energy based EV charging station in Libya,” *jsesd*, vol. 13, no. 2, pp. 311–349, 2024.

[66] A. Alsharif, A. A. Ahmed, M. M. Khaleel, A. S. Daw Alarga, O. S. M. Jomah, and I. Imbayah, “Comprehensive state-of-the-art of vehicle-to-grid technology,” in *2023 IEEE 3rd International Maghreb Meeting of the Conference on Sciences and Techniques of Automatic Control and Computer Engineering (MI-STA)*, 2023.

[67] A. A. Ahmed *et al.*, “Integrating renewable energy sources with electric vehicle infrastructure for enhanced renewability,” in *Proceedings of the EAI 3rd International Conference on Intelligent Systems and Machine Learning, ICISML 2024, January 5-6, 2024, Pune, India*, 2024.

[68] G. Harper *et al.*, “Recycling lithium-ion batteries from electric vehicles,” *Nature*, vol. 575, no. 7781, pp. 75–86, 2019.

[69] I. E. Atawi, A. Q. Al-Shetwi, A. M. Magableh, and O. H. Albalawi, “Recent advances in hybrid energy storage system integrated renewable power generation: Configuration, control, applications, and future directions,” *Batteries*, vol. 9, no. 1, p. 29, 2022.

[70] S. Arabi-Nowdeh *et al.*, “Multi-criteria optimal design of hybrid clean energy system with battery storage considering off- and on-grid application,” *J. Clean. Prod.*, vol. 290, no. 125808, p. 125808, 2021.
[71] M. F. Roslan *et al.*, “Techno-economic impact analysis for renewable energy-based hydrogen storage integrated grid electric vehicle charging stations in different potential locations of Malaysia,” *Energy Strat. Rev.*, vol. 54, no. 101478, p. 101478, 2024.
[72] D. Bukari, F. Kemausuor, D. A. Quansah, and M. S. Adaramola, “Towards accelerating the deployment of decentralised renewable energy mini-grids in Ghana: Review and analysis of barriers,” *Renew. Sustain. Energy Rev.*, vol. 135, no. 110408, p. 110408, 2021.
[73] M. Alam and S. Bhattacharyya, “Decentralized renewable hybrid mini-grids for sustainable electrification of the off-grid coastal areas of Bangladesh,” *Energies*, vol. 9, no. 4, p. 268, 2016.
[74] B. Ugwoke, A. Adeleke, S. P. Corgnati, J. M. Pearce, and P. Leone, “Decentralized renewable hybrid mini-grids for rural communities: Culmination of the IREP framework and scale up to urban communities,” *Sustainability*, vol. 12, no. 18, p. 7411, 2020.
[75] S. Bhattacharyya, “Mini-grids for the base of the pyramid market: A critical review,” *Energies*, vol. 11, no. 4, p. 813, 2018.
[76] R. Sen and S. C. Bhattacharyya, “Renewable energy-based mini-grid for rural electrification: Case study of an Indian Village,” in *Green Energy and Technology*, Cham: Springer International Publishing, 2014, pp. 203–232.
[77] A. Cabanero, L. Nolting, and A. Praktiknjo, “Mini-grids for the sustainable electrification of rural areas in sub-Saharan Africa: Assessing the potential of KeyMaker Models,” *Energies*, vol. 13, no. 23, p. 6350, 2020.
[78] H. Beath, J. Baranda Alonso, R. Mori, A. Gambhir, J. Nelson, and P. Sandwell, “Maximising the benefits of renewable energy infrastructure in displacement settings: Optimising the operation of a solar-hybrid mini-grid for institutional and business users in Mahama Refugee Camp, Rwanda,” *Renew. Sustain. Energy Rev.*, vol. 176, no. 113142, p. 113142, 2023.
[79] P. Shrestha, A. Shrestha, N. T. Shrestha, A. Papadakis, and R. K. Maskey, “Assessment on scaling-up of mini-grid initiative: Case study of mini-grid in rural Nepal,” *Int. J. Precis. Eng. Manuf.-Green Technol.*, vol. 8, no. 1, pp. 217–231, 2021.
[80] M. Gujar, A. Datta, and P. Mohanty, “Smart Mini Grid: An innovative distributed generation based energy system,” in *2013 IEEE Innovative Smart Grid Technologies-Asia (ISGT Asia)*, 2013, pp. 1–5.
[81] Erdiwansyah, Mahidin, M. Zaki, A. Gani, Muhibbuddin, and Jalaluddin, “A review of renewable energy mini-grid systems in the non-interconnected rural areas: A case study,” *Journal of Hunan University Natural Sciences*, vol. 48, no. 1, 2021.
[82] J. Gyimah, Y. Liu, G. Nyantakyi, and X. Yao, “The effect of mini-grid rural electrification on urbanization: Evidence from the pilot mini-grid systems in Ghana,” *Rev. Dev. Econ.*, vol. 28, no. 3, pp. 1108–1130, 2024.
[83] A. B. Marful, O. Kornyo, M. Asante, R. Opoku, D. Y. A. Duah, and B. Tei-Partey, “Integration of advanced metering infrastructure for mini-grid solar PV systems in off-grid rural communities (SoAMIRural),” *Sustainability*, vol. 15, no. 9, p. 7526, 2023.
[84] T. Castillo-Calzadilla, M. A. Cuesta, C. Olivares-Rodriguez, A. M. Macarulla, J. Legarda, and C. E. Borges, “Is it feasible a massive deployment of low voltage direct current microgrids renewable-based? A technical and social sight,” *Renew. Sustain. Energy Rev.*, vol. 161, no. 112198, p. 112198, 2022.
[85] T. Castillo-Calzadilla *et al.*, “Is a massive deployment of renewable-based low voltage direct current microgrids feasible? Converters, protections, controllers, and social approach,” *Energy Rep.*, vol. 8, pp. 12302–12326, 2022.
[86] P. K. Behera and M. Pattnaik, “Design and real-time implementation of wind–photovoltaic driven low voltage direct current microgrid integrated with hybrid energy storage system,” *J. Power Sources*, vol. 595, no. 234028, p. 234028, 2024.
[87] M. Nasir, S. Iqbal, and H. A. Khan, “Optimal planning and design of low-voltage low-power solar DC microgrids,” *IEEE Trans. Power Syst.*, vol. 33, no. 3, pp. 2919–2928, 2018.
[88] A. Sharma, S. Agrawal, and J. Urpelainen, “The adoption and use of solar mini-grids in grid-electrified Indian villages,” *Energy Sustain. Dev.*, vol. 55, pp. 139–150, 2020.