

Integrating Multi-Energy Microgrid Systems to Mitigate Energy Poverty in Remote Areas

Horcel M. K. Menga
FEUP, UPorto
Porto, Portugal
up202308551@edu.fe.up.pt

Gerardo J. Osório
C-MAST,
UBI
Covilha, Portugal
g_osorio@ubi.pt

João P. S. Catalão
SYSTEC-ARISE,
FEUP, UPorto
Porto, Portugal
catalao@fe.up.pt

Abstract—This work focuses on multi-energy microgrid systems (MEMG) for remote areas to face energy poverty mitigation. The study is based on renewable energy sources—solar, wind, and biomass—and evaluates the technical, economic, social, and environmental feasibility of using these systems. The study was carried out by reviewing literature using IEEE Xplore and Scopus databases. The results revealed that research and publications on MEMGs have increased significantly in 2021–2024. Moreover, the results were reviewed, in which 93% of the articles demonstrated MEMGs configurations and discussed energy access issues, whereas 5% discussed review assessments. Moreover, the results indicate that hybrid microgrids can provide a reliable and sustainable electricity supply, helping to improve the quality of life and socio-economic development in remote areas. Additionally, hybrid microgrids can contribute to sustainable development goals by reducing emissions and ensuring the security of energy supply. However, the challenges include high initial investment, regulatory obstacles, and others. The findings of this study have practical implications for addressing energy poverty in remote areas.

Index Terms—Energy poverty, Environmental sustainability, Multi-energy microgrid systems, Renewable resources.

I. INTRODUCTION

Energy poverty is still a major problem in remote areas because of the lack of access to reliable and affordable energy. More than 1.2 billion people don't have access to electricity, of which a significant number are living in rural areas of sub-Saharan Africa with an electrification rate of 35% or less according to IEA and IRENA [1].

No electricity access not only hinders economic development but also endangers people's lives in all aspects such as health and education, making poverty and inequality vicious circles [2]. More than 598 million people in Sub-Saharan Africa still lack access to electricity, and this exacerbates poverty and hinders socioeconomic development [3]. Lack of energy access hinders socioeconomic development and perpetuates poverty, as communities are unable to engage in activities that require energy resources [4].

The purpose of this review work is to analyse the recent research that has been conducted on MEMGs developed to support energy poverty challenges and to identify the challenges, barriers and opportunities for deployment. This review has identified case studies in Africa and technology developments that have shown the potential for these systems to support energy access in underserved communities [5].

This literature review focuses on the goal of researching MEMGs, discussing their solutions to energy poverty, and best practices for their applications in remote areas. It also discusses the main technological, economic, and social factors affecting their operation [2].

The study integrates results from various literature to, therefore, explain thoroughly how MEMGs can be effectively implemented in rural electrification programs. The significance of this research lies in the possibility of contributing to a sustainable development that improves the quality of life in isolated areas, providing access to electricity and subsequently other essential services such as health, education, and clean water, improving the living conditions [4], [6].

Furthermore, employing renewable technologies can contribute to environmental sustainability by reducing greenhouse emissions and promoting economic development through the creation of jobs [7]. Finally, this work underlines the importance of the development of energy solutions in transforming the lives of those living in energy poverty and enhancing humanity's development.

A. Challenges and Obstacles

In remote regions, challenges to providing reliable and affordable energy access are significant. Geographic isolation often results in high infrastructure development costs, making it economically unfeasible for utility companies to extend traditional grid systems [7]. Lack of infrastructure, such as roads and communications, further impedes the delivery and maintenance of energy [6]. Economic constraints, encompassing low-income levels and limited finances, hinder investment in energy solutions, leaving many communities without reliable energy sources [7].

G.J. Osório acknowledges the support by FCT through UIDB/00151/2020 (<https://doi.org/10.54499/UIDB/00151/2020>) and UIDP/00151/2020 (<https://doi.org/10.54499/UIDP/00151/2020>), C-MAST. J.P.S. Catalão acknowledges the support of the EU Horizon Europe Programme under GA ID: 101160614 (EU-DREAM Project, DOI: 10.3030/101160614).

B. Socioeconomic and Environmental Issues

The socioeconomic and environmental impact of energy poverty is severe. Lack of electricity access is linked to poor health outcomes, such as indoor air pollution from burning traditional biomass fuels for cooking, which leads to respiratory diseases [1], [2]. Similarly, energy poverty restricts educational opportunities and economic opportunities, maintaining poverty cycles and inequality, and has an environmental impact, as communities often resort to unsustainable practices, such as deforestation for firewood, which contributes to climate change and biodiversity loss [7].

C. Advantages and Limitations of Different RES

Significant RES available in remote areas include solar, wind, hydropower, biomass, and diesel generators. Solar energy has emerged as the favoured option for off-grid electrification owing to its technical suitability and increasingly cost-effective nature. Wind energy is also suitable in some areas depending on the site conditions [8]. Hydropower can deliver reliable energy, subject to water availability and topography, [9]. Biomass [10] is a conventional source of energy in many regions, although its sustainability is under threat due to overexploitation while diesel generators provide immediate power but are expensive and contribute to greenhouse gas emissions [5]. These RES have their advantages and limitations, addressed in TABLE I.

As a solution, MEMGs can help overcome energy poverty in a rural area by integrating different energies such as solar, wind [8], biomass and diesel generators to satisfy the energy requirements of a community [11]. MEMGs can minimize the rural community's reliance on fossil fuels, minimize the cost of energy, and increase energy security by using locally available RES in rural areas [9]. MEMGs are a distributed energy system that integrates most energy-supplying resources locally to enhance the reliability and security of the energy system. RES generation with energy storage, and control technologies constitute the heart of the MEMGs [12].

D. Technological Developments and Benefits in MEMGs

By integrating generation, storage, and control technologies, MEMGs can create a more reliable energy supply that can be operated independently or in conjunction with the main grid. MEMGs have the potential to bring many benefits to remote areas, including improved energy reliability, higher RES penetration and lower energy costs for consumers [13]. They also have the potential to improve energy security, decrease dependence on fossil fuels, and reduce environmental impact by using local resources [8]. Recent technical developments such as smart grids, advanced storage, power electronics, and control technologies have also enhanced the performance and feasibility of microgrid systems [10].

E. Emerging Technologies Integrated in MEMGs

Some of the latest technologies in the field of MEMGs include the development of energy storage technology, lithium batteries for RES reliability, power electronics, and control technology in the field of enhancing the integration and management of various energy sources [3]. Emerging technologies, including blockchain, artificial intelligence (AI), and the Internet of Things (IoT) are being used more and more in MEMGs applications.

TABLE I. ADVANTAGES AND LIMITATIONS OF RES TECHNOLOGIES

RES	Advantages	Limitations	Ref.
Solar Energy Systems	- Scalability - Quick to deploy - Suitable for remote areas - Low maintenance	- Dependence on sunlight - Energy storage required	[6], [7]
Wind Energy Systems	- Substantial power generation - Environmental friendliness	- Variability in wind speed - Location requirements	[6], [8],
Hydropower	- Reliability and Continuous Supply - Energy Storage	- Environmental Impact	[8], [9]
Biomass	- Continuous energy supply - Waste management	- Disputes about food production - Labor-intensive	[10], [11]

Blockchain can assist in peer-to-peer energy trading, while AI can be used to optimize energy management and predictive maintenance [6]. IoT devices can be used to monitor and control the energy system in real-time, improving operational efficiency and user engagement [8].

F. Socioeconomic and Environmental Benefits of Technological Development

MEMGs can provide permanent access to electricity in support of local businesses, education, and health care [10], [14], [15], [16]. Environmentally, MEMGs can help reduce greenhouse gas emissions and encourage sustainable energy sources [9]. By using RES, MEMGs also help to mitigate the effects of climate change and promote environmental stewardship [1].

G. MEMGs: An Enabler for Sustainable Development Goal

MEMGs can contribute significantly to multiple SDGs, especially SDG 7 (affordable and clean energy) by providing greater energy access to isolated regions with renewable resources [3]. This energy delivery is vital for universal electricity access in regions where traditional grid infrastructure is unavailable. [17]

These systems reduce fossil fuel dependence while promoting clean energy and ensuring affordable, reliable, sustainable, and modern energy for all. MEMGs contribute to SDG 13 (climate action) by reducing emissions as it shifts from fossil fuels to renewables, SDG 10 (reduced inequalities) by expanding energy access to the underserved, empowering the vulnerable and creating renewable jobs locally [2], [4], [9].

MEMGs also support SDG 12 (responsible consumption and production) by encouraging efficient use of local renewables, reducing transmission loss, and creating a renewable energy culture [6].

Beyond these direct contributions, MEMGs can have indirect contributions to other SDGs. By providing energy access, MEMGs can enable local businesses to improve livelihoods, contributing to SDG 1 (poverty reduction) and SDG 8 (economic growth). The integration of community participation and engagement in MEMGs design and implementation can also promote social equity and empowerment, aligning with the goals of SDG 10 (reducing inequality) [10].

II. METHODOLOGY

This work review adopts a systematic approach to explore the role of MEMGs in mitigating energy poverty in remote areas. The methodology employed a detailed review of existing literature on empirical studies, theoretical frameworks, and case studies illustrating the role of MEMGs on energy access with a focus on unsolved issues and future direction.

Objective and Research Scope: The main objective is to review recent research on the MEMGs developed to serve energy poverty challenges, to identify challenges, barriers, and opportunities for MEMGs deployment and to identify future trends. The review includes research manuscripts, conference manuscripts, reports and others, considering the last five years of research on energy access in remote areas.

Review Search Strategy: A systematic search was conducted to identify relevant literature from various sources including Google Scholar, IEEE Xplore, ScienceDirect, Scopus, Springer and Web of Science. The search keywords were “energy poverty”, “multi-energy”, “microgrid systems”, “renewable energy” and “environmental sustainability”. The search was limited to English-language publications.

Selection Criteria: The review was selected based on inclusion and exclusion criteria. The filter focused on analysing article titles, abstracts and conclusions to determine the relevancy and timeliness of the findings. Only studies based on RES, microgrids and energy poverty that have been peer-reviewed for further consideration were considered.

Data Synthesis and Analysis: Relevant information was extracted from the selected articles, including publications years, research methods employed, significant findings, challenges, barriers, opportunities and future trends identified. The initial search retrieved 150 documents but applied exclusion criteria and analysed the abstracts and conclusions, in some instances reducing the number to 40 documents.

As shown in Fig. 1, 83% of the 40 references were journal manuscripts, 10% were books, 5% review manuscripts, and 2% were conference manuscripts. Fig. 2 shows the last research results over the period 2021 to 2025 considering the mix of MEMGs and energy poverty. From this, the investigation kept 32 references for this review.

TABLE II resumes some of the successful projects implemented, mainly in Africa [18]-[31], promising solutions in terms of integration of RES, low cost and environmental benefits, with several challenges and gaps to consider, which include long-term sustainability, socio-political integration, community involvement, high initial cost and supportive policies, and empirical data. Hence, the projects are focused on these areas to fully realize the potential of MEMGs in Africa.

III. OVERVIEW OF THE RESULTS AND DISCUSSION

A. Key Findings from Literature Review

Energy poverty has severely hindered the social and economic development in remote African areas as stated previously [1]. MEMGS is a practical solution for energy poverty in underdeveloped areas. Literature usually integrates a variety of power sources such as RES, and energy storage devices to provide reliable and sustainable power [3].

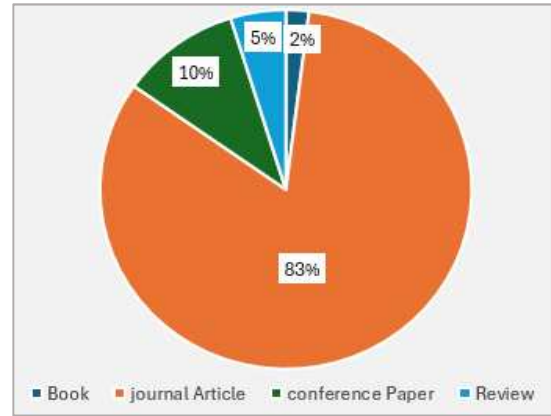


Figure 1. Distribution of reference type included in the review.

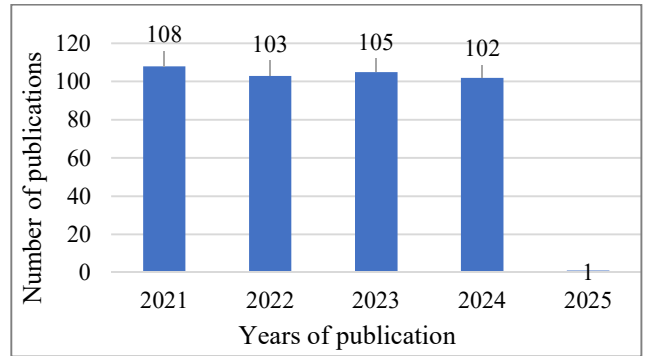


Figure 2. The trend of MEMGs vs Energy Poverty period from 2021 to 2025.

Hybrid microgrid systems combining multiple RES can improve energy reliability and reduce costs [10]. Moreover, several case studies also illustrate that hybrid microgrid systems can mitigate greenhouse gas emissions for better environmental sustainability [3].

B. Technological Advancements in MEMGs

Innovations in energy storage such as batteries and hydro pumped have improved the reliability of RES, addressing intermittency [8]. Advancements in power electronics and control systems improved the integration and management of multiple energy sources in microgrids, enhancing efficiency and responsiveness to local energy needs [18]. Hence, the integration of emerging technologies such as blockchain, AI, and IoT provides enhanced data management, predictive maintenance, and optimized energy distribution, improving overall performance [2].

C. Socioeconomic and Environmental Impacts of MEMGS in Remote Regions

The socioeconomic benefits of MEMGs in remote areas are remarkable. Access to electricity increases health outcomes, improves educational opportunities, and promotes economic activities for poverty reduction in these areas [6], like enhancing the job creation and bustling local economic activities have been observed with the connection of microgrids. Environmentally, using RES results in a reduction in GHG emissions [3], [4].

TABLE II. SUMMARY OF SOME EXISTING RESEARCH ON MEMGS VS. ENERGY POVERTY

Ref	Topic	MG configuration	Key Findings	Research Gaps
[2]	Energy Poverty Relief in Zambia	Biogas/SPV, Battery	- Energy access has socio-economic benefits in rural areas - Relationship between energy access/ poverty relief. Replace wood/ fossil fuels	- Lack of clear comprehensive policy to support implementation. Socio-economic conditions in the areas are not considered. The financing cost is high for hybrid RES.
[4]	RES potential in rural Africa	PV, Wind, Biomass	- Hybrid mini-grids provide energy access, bridge the energy access gap, and support a low-carbon economy	- High upfront costs make hybrid prohibitively expensive. Lack of investment is a barrier to hybrids. - Require empirical evidence of the performance of the hybrid in different settings.
[5]	Energy poverty and Economic Growth	HRES	- Improving energy access can significantly boost economic growth in Sub-Saharan Africa.	- Insufficient data on the longer-term economic impacts of energy access to rural communities.
[6]	MG Feasibility	PV, WT, Biomass, Hydro, DG, battery	- Hybrid system supplies the required energy - The system was economically feasible - Shown RES integration in remote areas	- Socio-political factors influencing microgrid implementation were overlooked. - Limited consideration for future load demand growth. - Insufficient focus on long-term sustainability.
[10]	MEMGS	SPV, Battery, BG, DG	- Guarantee of uninterrupted power supply - Minimize GHG emissions	- Externality is not considered when calculating the local cost of energy (LCOE). - Not sustainable over the long term in varying climatic conditions
[12]	RES-Based Mini-Grids in Africa	Improve energy access in Africa	- Gap between supply and demand - Reliable access to energy for rural people	- High upfront capital costs, with political, economic, and social barriers.
[13]	Energy Poverty Alleviation	Sola, Biomass	- Reduced poor and vulnerable people - Increased small-scale industries	- Limited geographical scope. - Longitudinal study impact on the long term.
[16]	Energy Poverty and Economic Development	Energy poverty vs development	- Explores the linkages between energy poverty and economic development and emphasizes the importance of access to clean energy.	- Under-explores the long-term economic impacts of energy poverty interventions
[20]	Energy poverty vs health	Biogas, Solar PV	- Energy poverty is detrimental to health - Solid biomass fuels dominate in Ghana	- Energy poverty's effects on long-term health are insufficiently studied.
[21]	Economic analysis of MEMGS	SPV, DG, Wind	- Cost-effective - Environmentally friendly - Low net present cost	- Lack of data for long-term sustainability. - Lack of data for the cost of maintenance, long-term performance, and scalability
[22]	Feasibility of MEMGS	PV, Wind, Biogas, Geothermal	- Dual-axis solar tracker improved energy production - Highlighted environmental benefits	- The study does not address the long-term operational challenges of hybrid systems
[23]	Feasibility of MEMGS	PV, Wind, Biomass	- Proved economical for rural electrification	- Lack of detailed environmental impact analysis. - Need a diverse set more case studies across regions.
[24]	Community engagement in mini-grid projects	The success of solar mini-grid projects in Sierra Leone.	- Community influences the perceived benefits of RE on poverty	- Reduction of Small sample size and geographic focus.
[25]	MEMGS in South Africa	SPV, Wind, DG, Batteries in South Africa.	- Low cost, High renewable fraction - Low emissions	- Financial and resources are urgent for policy increase. - Technical challenges in advanced integration.
[26]	Energy poverty vs Infrastructure	HRES	- Energy poverty and infrastructure development reduce energy poverty.	- Studies are needed to identify the specific type of infrastructure investments.
[27]	Energy poverty and Economic Growth	Energy poverty vs economic	- Higher GDP is positively associated with electricity access. - Energy-related aid has no significant effect on electricity access	- Further research can be used to test if energy aid is beneficial in rural areas.
[28]	Energy poverty in Urban Areas	Energy poverty vs remote area	- Energy poverty doesn't exist only in rural areas. - 34% of urban households are in energy poverty	- Limitation on the socio-political implications of energy poverty in urban settings
[29]	Energy Poverty and Health in Sub-Saharan Africa	Energy poverty vs Health	- The study examines the links between energy poverty and health outcomes, looking at infant and child and maternal mortality	- Lack of qualitative data to support the findings - Future work is suggested on governance challenges in electricity access
[30]	Energy Poverty	Energy Poverty vs urbanization	- Urbanization influences energy poverty economic and infrastructure urbanization help reduce energy poverty	- Demographic, social and ecological urbanization do not influence alleviating energy poverty.
[31]	Energy Poverty in Sub-Saharan Africa	Energy poverty vs Africa	- This study uses the poverty gap index to measure poverty, finding significant energy poverty in Sub-Saharan Africa - Energy poverty in Sub-Saharan Africa is hampering socio-economic development	- More disaggregated data is needed to better understand the impact of energy poverty on Sub-Saharan Africa.

D. Challenges and Barriers to MEMG Adoption

One of the challenges found is the skilled manpower for designing, implementing, and maintaining these systems. The complexity of integrating different energy sources and ensuring MEMGs reliability under varying conditions [9], [19]. Another challenge is the high initial capital costs of establishing the microgrid system and so, rural communities cannot afford MEMGs as well as the lack of policies that do not cover the development of decentralized energy systems [4], [20].

Other issues are related to community acceptance and awareness of RES technologies, as well as capacity building and community engagement. While MEMGs provide a promising solution to energy poverty in remote areas, overcoming the challenges associated with its implementation will be essential for successful deployment and long-term sustainability [19], [21].

Further research and investment in technology, policy frameworks, as well as community engagement and education will be critical in addressing these barriers and realizing the full potential of multi-energy microgrid systems [9]. The related work has examined some studies in MEMGs integration to address energy poverty in remote areas.

Energy poverty brings many challenges to socio-economic development for the community, especially in African rural areas, where there still is less than 15% in some areas for electricity access [21]. The studies showed that RES integration is a key technology for providing sustainable and reliable energy, considering solar, wind, and biomass integration in such areas, reducing significantly the access costs to the main grid [3].

The studies have also shown that the amalgamation of multiple energy sources in hybrid microgrid systems like MEMGs, may provide energy reliability and lower cost compared to an extended grid [2]. Hence, it could be a great opportunity for international investment and study, implementing real cases applications, promoting international diplomacy, and increasing the robustness and findings shown in published projects.

E. Limitations and Prospects for Future Research

The findings are derived mainly based on theoretical models and simulations and may not be representative of real-life conditions. Social and cultural factors not adequately explored may affect the acceptance and success of multi-energy microgrids in different communities [6], [32]. Also, there is a lack of study related to the initial capital costs associated with the deployment of MEMGs systems. [12]

Even though technical and economic aspects are commonly addressed, the social and cultural aspects are also commonly ignored, which may affect the acceptance and sustainability of MEMGs projects [1], [2], [12]. MEMGs require technical expertise for installation and maintenance. Also, the regulatory and policy challenges that restrict the development of MEMGs systems are not enough to support the incentives [20]. Future research includes:

- Empirical studies to understand the performance and impact of deployed MEMGs in the context and its cost-effective solutions,

- Exploring the impact of socio-economic factors on the deployment and sustainability of microgrids and the role of community engagement and local government in its implementation,
- Evaluating the scalability of microgrids in different geographies and socio-economic conditions to identify best practices for wider adoption,
- Developing policy frameworks for supporting microgrids in remote areas. Exploring the role of emerging technologies such as blockchain and IoT for MEMGs.

IV. CONCLUSION

MEMGs-integrated RES like solar, wind and biomass are a promising solution for energy poverty in remote areas. These systems provide reliable and sustainable electricity, which is a critical factor for rural community socioeconomic development. The deployment of renewable energy-based microgrid systems is considered a reliable solution for supplying power to rural communities, improving their quality of life, and creating job opportunities. Smart grids and advanced energy management systems can be integrated into microgrids for more efficient and reliable operation. Moreover, MEMGs have the potential to contribute to sustainable development and the achievement of SDGs.

These systems can directly support SDG 7, which aims to ensure access to affordable, reliable, sustainable, and modern energy for all. By facilitating the transition to RES, microgrids contribute to SDG 13 by reducing greenhouse gas emissions from traditional energy sources. Furthermore, by integrating community engagement in the design and implementation of these systems, social equity and empowerment are vastly promoted, realizing SDG 10, which focuses on reducing inequalities.

Future research should focus on developing affordable solutions and policies for the deployment of microgrids in remote areas. Emerging technologies such as blockchain and IoT could play an important role in optimizing microgrids' operation and management. Policymakers should develop supportive regulatory and financial frameworks that encourage investment in the microgrid infrastructure.

Community engagement and capacity building should also be considered a priority to ensure the successful implementation and sustainability of microgrids. Addressing energy poverty requires further effort and innovation like multi-energy microgrids. Multi-energy microgrids not only bring benefits to energy access but also contribute to long-term sustainable development goals. MEMGs reduce dependence on fossil fuels and promote renewable energy development, which can mitigate climate change and support environmental sustainability. Therefore, it is important to maintain the momentum of research, policy, and implementation of MEMGs to help remote communities benefit from them.

REFERENCES

- [1] W. Leal Filho et al., "Energy poverty in African countries: An assessment of trends and policies," *Energy Research & Social Science*, vol. 117, p. 103664, Nov. 2024, doi: 10.1016/j.erss.2024.103664.

- [2] M. Murshed and I. Ozturk, "Rethinking energy poverty reduction through improving electricity accessibility: A regional analysis on selected African nations," *Energy*, vol. 267, p. 126547, Mar. 2023, doi: 10.1016/j.energy.2022.126547.
- [3] Y. Liu and Z. Bah, "Enabling development impact of solar mini-grids through the community engagement: Evidence from rural Sierra Leone," *Energy Policy*, vol. 154, p. 112294, Jul. 2021, doi: 10.1016/j.enpol.2021.112294.
- [4] E. Mudaheranwa, E. Ntagwirumugara, G. Masengo, and L. Cipcigan, "Microgrid design for disadvantaged people living in remote areas as tool in speeding up electricity access in Rwanda," *Energy Strategy Reviews*, vol. 46, p. 101054, Mar. 2023, doi: 10.1016/j.esr.2023.101054.
- [5] F. Belaïd and V. Flambard, "Impacts of income poverty and high housing costs on fuel poverty in Egypt: An empirical modeling approach," *Energy Policy*, vol. 175, p. 113450, Apr. 2023, doi: 10.1016/j.enpol.2023.113450.
- [6] I. K. Sule, A. M. Yusuf, and M.-K. Salihu, "Impact of energy poverty on education inequality and infant mortality in some selected African countries," *Energy Nexus*, vol. 5, p. 100034, Mar. 2022, doi: 10.1016/j.nexus.2021.100034.
- [7] U. G. Onu, G. S. Silva, A. C. Zambroni De Souza, B. D. Bonatto, and V. B. Ferreira Da Costa, "Integrated design of photovoltaic power generation plant with pumped hydro storage system and irrigation facility at the Huelem-Amoncha African community," *Renewable Energy*, vol. 198, pp. 1021–1031, Oct. 2022, doi: 10.1016/j.renene.2022.08.059.
- [8] Y. Liang et al., "Techno-Economic Feasibility of Off-Grid Renewable Energy Systems: A Comparative Case Study," in *IECON 2023- 49th Annual Conference of the IEEE Industrial Electronics Society*, Singapore, Singapore: IEEE, Oct. 2023, pp. 1–6, doi: 10.1109/IECON51785.2023.10312184.
- [9] M. H. Saeed, W. Fangzong, B. A. Kalwar, and S. Iqbal, "A Review on Microgrids' Challenges & Perspectives," *IEEE Access*, vol. 9, pp. 166502–166517, 2021, doi: 10.1109/ACCESS.2021.3135083.
- [10] A. Balobaid, W. M. Abd-Elhafiez, S. M. Nagy, and D. W. Trabay, "Integrating Multi-Criteria Decision-Making Techniques in Assessing Renewable Energy Potential: A Case Study of Egypt," *IEEE Access*, vol. 12, pp. 103594–103605, 2024, doi: 10.1109/ACCESS.2024.3434604.
- [11] O. Khaled, M. Zahid, T. Zahid, and T. Ilahi, "Techno-Economic Feasibility of Hybrid Energy Systems Installation in Pakistan," *IEEE Access*, vol. 12, pp. 41643–41658, 2024, doi: 10.1109/ACCESS.2024.3376409.
- [12] V. Motjoadi and P. N. Bokoro, "Improving Electricity Supply Reliability: A Case Study of Remote Communities of Limpopo in South Africa," in *Recent Advances in Energy Systems, Power and Related Smart Technologies*, vol. 472, K. Kyamakya and P. N. Bokoro, Eds., in *Studies in Systems, Decision and Control*, vol. 472, Cham: Springer Nature Switzerland, 2024, pp. 135–174, doi: 10.1007/978-3-031-29586-7_6.
- [13] A. Abu-Rayash and I. Dincer, "Development and assessment of an integrated wind-solar based energy system for sustainable communities," *Energy Conversion and Management*, vol. 277, p. 116680, 2023, doi: <https://doi.org/10.1016/j.enconman.2023.116680>.
- [14] K. Rajesh, A. Ramkumar, and S. Rajendran, "Generation Expansion Planning Using Renewable Energy Sources with Storage," in *Recent Advances in Energy Systems, Power and Related Smart Technologies*, vol. 472, K. Kyamakya and P. N. Bokoro, Eds., Cham: Springer Nature Switzerland, 2024, pp. 53–101, doi: 10.1007/978-3-031-29586-7_3.
- [15] F. Vandeninden, R. Grun, and F. Fecher, "Energy subsidies and poverty: The case of fossil fuel subsidies in Burkina Faso," *Energy for Sustainable Development*, vol. 70, pp. 581–591, Oct. 2022, doi: 10.1016/j.esd.2022.08.023.
- [16] B. Xin, T. Zhang, and E. D. R. Santibanez-Gonzalez, "Synergistic effects of regional environmental governance on alleviating energy poverty and promoting household decarbonization," *Energy Policy*, vol. 185, p. 113970, Feb. 2024, doi: 10.1016/j.enpol.2023.113970.
- [17] T. Kataray et al., "Integration of smart grid with renewable energy sources: Opportunities and challenges – A comprehensive review," *Sustainable Energy Technologies and Assessments*, vol. 58, p. 103363, Aug. 2023, doi: 10.1016/j.seta.2023.103363.
- [18] M. A. Hannan et al., "Recent advancement of energy internet for emerging energy management technologies: Key features, potential applications, methods and open issues," *Energy Reports*, vol. 10, pp. 3970–3992, Nov. 2023, doi: 10.1016/j.egy.2023.10.051.
- [19] M. Ashraf Islam et al., "Assessing the feasibility and quality performance of a renewable Energy-Based hybrid microgrid for electrification of remote communities," *Energy Conversion and Management: X*, vol. 23, p. 100674, Jul. 2024, doi: 10.1016/j.ecmx.2024.100674.
- [20] C. Bukari, S. Broermann, and D. Okai, "Energy poverty and health expenditure: Evidence from Ghana," *Energy Economics*, vol. 103, p. 105565, Nov. 2021, doi: 10.1016/j.eneco.2021.105565.
- [21] L. Makai and O. Popoola, "Assessment and selection of a micro-hybrid renewable energy system for sustainable energy generation in rural areas of Zambia," *Renewable Energy*, vol. 232, p. 121036, Oct. 2024, doi: 10.1016/j.renene.2024.121036.
- [22] J. Bloomer and D. Boateng, "Prepaid into poverty? Exploring energy poverty and access to alternative electricity sources among urban poor households in Ghana," *Energy Research & Social Science*, vol. 112, p. 103510, Jun. 2024, doi: 10.1016/j.erss.2024.103510.
- [23] B. A. Medjo Nouadje, P. Tiam Kapen, V. Chegnimonhan, and R. Tchinda, "Techno-economic analysis of an islanded energy system based on geothermal/biogas/wind/PV utilizing battery technologies: A case study of Woulde, Adamawa's region, Cameroon," *Energy Strategy Reviews*, vol. 54, p. 101469, Jul. 2024, doi: 10.1016/j.esr.2024.101469.
- [24] H. Wirawan and Y. M. L. Gultom, "The effects of renewable energy-based village grid electrification on poverty reduction in remote areas: The case of Indonesia," *Energy for Sustainable Development*, vol. 62, pp. 186–194, Jun. 2021, doi: 10.1016/j.esd.2021.04.006.
- [25] V. Buenfil Román, G. A. Espadas Baños, C. A. Quej Solís, M. I. Flota-Bañuelos, M. Rivero, and M. A. Escalante Soberanis, "Comparative study on the cost of hybrid energy and energy storage systems in remote rural communities near Yucatan, Mexico," *Applied Energy*, vol. 308, p. 118334, Feb. 2022, doi: 10.1016/j.apenergy.2021.118334.
- [26] W. Benayed, H. Awijen, R. Bousnina, and M. A. Chroufa, "Infrastructure for sustainable energy access in Sub-Saharan Africa: Leveraging social factors and natural capital," *Journal of Cleaner Production*, vol. 470, p. 143304, Sep. 2024, doi: 10.1016/j.jclepro.2024.143304.
- [27] D. Li, J. H. Bae, and M. Rishi, "Sustainable Development and SDG-7 in Sub-Saharan Africa: Balancing Energy Access, Economic Growth, and Carbon Emissions," *Eur J Dev Res*, vol. 35, no. 1, pp. 112–137, Feb. 2023, doi: 10.1057/s41287-021-00502-0.
- [28] M. A. Ugembe, M. C. Brito, and R. Inglesi-Lotz, "Measuring energy poverty in Mozambique: Is energy poverty a purely rural phenomenon?," *Energy Nexus*, vol. 5, p. 100039, Mar. 2022, doi: 10.1016/j.nexus.2022.100039.
- [29] M. Byaro, N. F. Mmbaga, and G. Mafwolo, "Tackling energy poverty: Do clean fuels for cooking and access to electricity improve or worsen health outcomes in sub-Saharan Africa?," *World Development Sustainability*, vol. 4, p. 100125, Jun. 2024, doi: 10.1016/j.wds.2024.100125.
- [30] X. Qi, J. Chen, J. Wang, H. Liu, and B. Ding, "The impact of urbanization on the alleviation of energy poverty: Evidence from China," *Cities*, vol. 151, p. 105130, Aug. 2024, doi: 10.1016/j.cities.2024.105130.
- [31] S. D. Ssekibaala and T. A. Kasule, "Examination of the poverty-environmental degradation nexus in Sub-Saharan Africa," *Regional Sustainability*, vol. 4, no. 3, pp. 296–308, Sep. 2023, doi: 10.1016/j.regsus.2023.08.007.
- [32] C.-C. Lee, Z. Yuan, C.-C. Lee, and Y.-F. Chang, "The impact of renewable energy technology innovation on energy poverty: Does climate risk matter?," *Energy Economics*, vol. 116, p. 106427, Dec. 2022, doi: 10.1016/j.eneco.2022.106427.