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Research Article

Integrating Solar Photovoltaic Power Source and Biogas Energy-Based System for Increasing Access to Electricity in Rural Areas of Tanzania

Isaka J. Mwakitalima,[1,2] **Mohammad Rizwan**,[1] **and Narendra Kumar**[1]

[1]*Department of Electrical Engineering, Delhi Technological University, Delhi, India*
[2]*Department of Electrical and Power Engineering, Mbeya University of Science and Technology, Mbeya, Tanzania*

Correspondence should be addressed to Isaka J. Mwakitalima; mwakitalimaisaka0@gmail.com

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Renewable energy is the best option for the challenge of dwindling natural resources and energy scarcity. The utilization of solar photovoltaic (PV) systems is the best option for eliminating the energy deficit in Tanzania due to the available great potential of solar energy. Animal manure is a significant source of waste in rural locations which can be transformed into biogas fuel by an anaerobic process. Livestock and agriculture greatly support economically the majority of the sub-Saharan African (SSA) region's rural population including Tanzania, and excreta from cattle are beneficial for biogas fuel production. Unfortunately, the high potential of animal waste for generating electricity is underutilized. Integrating solar energy sources and biogas fuel derived from animal manure is useful for mitigating energy shortage, power instability, and environmental issues. Off-grid solar PV biogas-based hybrid microgrid systems for rural electrification applications in the Tanzanian environment are limited, and also, most of the studies are extensively carried out using soft computing tools especially hybrid optimization of multiple energy resources (HOMER) software with limited applications of artificial intelligence (AI) optimization techniques. This paper presents technoeconomic viability analysis for a hybrid renewable energy supply system (HRESS) for the Simboya village in Mbeya region, Tanzania. Off-grid HRESS is designed and optimized to meet the load of the chosen location executed using HOMER software and the grey wolf optimization (GWO) method. The microgrid is anticipated to supply daily maximum demand of 63.41 kW. The residential load profile equals 30 kW representing 50% of the daily demand. Optimization results by the HOMER platform indicate that the system has a total net present cost (NPC) and levelized cost of energy (LCOE) of \$106,383.50 and \$0.1109/kWh, respectively. Furthermore, this paper presents the optimization and sensitivity analysis results acquired by the GWO method under varied values of Loss of Electrical Power Probability (LEPP). Total NPC and LCOE based on LEPP values of 0, 0.04, and 0.06 are \$85,106.8, \$79,545.99, and \$71,747.36 and \$0.0887/kWh, \$0.0316/kWh, and \$0.0102/kWh, respectively. HRESS is economically and environmentally beneficial for supplying electricity to the selected area and worldwide in similar situations.

1. Introduction

Energy plays a great role in giving premium socioeconomic services in any society. Energy utilization improves the social quality of life and simplifies the productivity of economic activities. The need for electricity is well known worldwide. It is described by the United Nations as a sustainable development goal and is stipulated as "Goal 7." The goal ensures the accessibility to reliable, inexpensive, up-to-date, and sustainable energy [1]. Decentralized energy systems are more favoured than grid power networks because the system is not cost-effective [2]. Moreover, fossil fuels are costly, and their reserves are finite and depletive. These nonrenewable fuels are also not ecologically friendly. In other words, the utilization of fossil fuels causes adverse impacts of pollution and global warming [3]. Developing countries face a major problem of energy shortage in rural areas where there is no grid coverage. Increased population and economic activities in these developing countries cause further energy deficit. Majority of developing countries solve this energy gap in rural areas by installing diesel generators. According to the aforementioned issues associated with fossil fuels, the generation of electricity by diesel generators is not economically viable and environmentally friendly. Because of that, alternative energy sources are essential for sustainable development [4]. Likewise, Tanzania as one of the SSA countries has a total estimated population of 58 million of which 20% represents urban while 80% indicates rural residents. Approximately 30% of all inhabitants in the country have access to an electric grid [5]. A large percentage of the population residing in countryside areas has a high demand for electricity, and it is undesirable. Diesel generators have been implemented to counteract the insufficiency of power supply in remote and rural areas. Nevertheless, this approach to rural electrification is costly and polluting [6]. This energy scenario can be improved using abundant renewable energy resources available in the country [6]. Unfortunately, the high potential of these energy sources is underutilized [6]. Renewable energy sources such as solar, wind, small hydro, and biomass can be used for off-grid power systems for remote and rural regions. Renewable energy sources are intermittent in nature causing power output variability. Reliability, energy management, and cost issues of these renewable sources can be addressed using energy storage equipment and configuration of hybrid technology (HRESS) to generate power for rural applications [7]. Besides, the potential of existing renewable energy resources is geographically dependent. Thus, an optimal size of HRESS is required for proper performance and cost-effectiveness. Various studies have been performed regarding HRESS in different locations worldwide [7]. The main goal of this research is to attain the finest arrangement of HRESS based on local resources for specific isolated rural areas in Tanzania. The study offers an economic comparative analysis of biogas generators versus DG in hybrid solar PV, considering biogas generators as cost-effective for the feasibility of replacing DG which is limited in the rural areas of the SSA region. In the first phase of this study, technoeconomic analysis is performed using HOMER software for dissimilar configurations which are anticipated to provide electricity at the proposed location and compares them using a financial indicator known as net present cost (NPC) in the life of 25 years. Such a study could be useful for the formulation of energy policies and decision-making for commercial strategy and implementation of hybrid biogas energy sources for providing access to electricity in rural areas in the country. In order to get this goal, the following are the specific objectives of the methodology: (i) identifying and proposing the rural site without grid connectivity, (ii) pinpointing the local renewable resources and realizing their potential, (iii) assessing the energy demand for the proposed off-grid site, and (iv) modelling, system sizing optimization, and opting for the superior cost-effective HRESS. Figure 1 indicates the comprehensive approach of the study. Presently, the use of metaheuristic techniques is a new area which is being highly explored by many researchers. In particular, to the best of the authors' experience and related theory, in the Tanzanian environment, the majority of the studies carried out on the HRESS have been executed using HOMER software. The applications of metaheuristic approaches are limited or at all are yet to be executed. For this reason and by considering the trend of modern researches, this particular study involves the use of both HOMER Pro software and an advanced metaheuristic approach called grey wolf optimizer (GWO). The GWO approach is one of the AI optimization techniques with successful working capability. In the second phase of the study, the GWO technique is deployed and validated by HOMER software. It is beyond the scope of this study to compare all the existing techniques. Nonetheless, the application of GWO has merits such as simplicity, flexibility, derivation which is not required during the optimization process, and avoidance of local optima due to its stochastic nature of GWO [8]. The GWO technique is greatly appropriate for solving complex nonlinear, multiadjustable, and multimodal function optimization problems. In short, the technique has high exploration capability with good equilibrium between global and local spaces [9].

The next part of this paper of research is organized as follows: Related literature review is presented in Section 2. The methodology is expounded in Section 3. Section 4 provides the descriptions of components and design of off-grid HRESS. Modelling of amalgamated power systems is explained in Section 5. Economic and technical input data of the proposed off-grid HRESS are represented in Section 6. The strategy for managing off-grid HRESS is presented in Section 7. Optimization of off-grid HRESS using the GWO method is discussed in Section 8. System reliability and sensitivity analysis using the GWO algorithm are described in Section 9. Results and discussions are elaborated on in Section 10. Comparisons of findings from other sources of related configurations are discussed in Section 11. Conclusions, recommendations, and research in the future are provided in Section 12. Declarations and statements, acknowledgments, and references follow.

2. Related Literature Review

This section presents a related theory of providing electricity to rural and isolated locations using renewable energy-based systems so as to increase access to electricity at local and global levels. The theory starts by giving highlights on the situation of the energy sector in Tanzania. This section also provides a brief description of using renewable energy sources for rural electrification in the country, the emphasis being on the utilization of solar and biogas energy sources. Related literature review is also furthered extensively to scrutinize the use of renewable energy sources for rural electrification worldwide. The review is presented as follows.

2.1. Status of Access to Energy in Tanzania. The global electrification rate is currently 82%. While developing countries as a whole have an electrification rate of 76%, the SSA region has fewer than 35%. More than 85% of Tanzania's population relies on wood-based energy (in the form of firewood and charcoal) for cooking and heating [10, 11]. Overdependence on biomass is frequent in rural and remote areas of

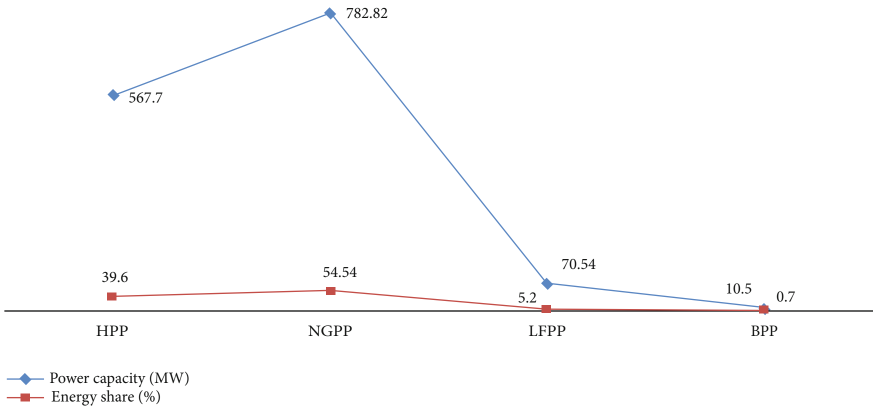

Figure 1: Electrical power generation mix in Tanzania.

Africa without access to electricity, accounting for 80% of the continent's population [10]. Tanzania is one of the five nations of the African continent that have the lowest electrification rates with an estimated electrification rate of 14%, and more than 37 million people have no access to modern energy including electricity [10]. This, in turn, has negative effects on other aspects of human development, such as child mortality and health-related difficulties. Tanzania, on the other hand, provides a diverse range of renewable energy sources, including biomass, solar, wind, geothermal, and hydropower [10, 11]. However, the majority of these resources have not been accessible or sufficiently exploited by the government or individuals. Tanzania's state capacity is limited, with poor service delivery of critical public goods such as energy, health, education, and water. Apart from the efforts which are made by the government, the Tanzanian government's inability to deliver sufficient energy to a booming population will most certainly continue to be a challenge for decades to come [10]. Tanzania is a big country with a dispersed and low-density population making the connectivity to the main grid expensive, especially given the poor productivity of rural areas which presents a limited economic benefit for a centrally designed infrastructure [10]. Furthermore, connection to Tanzania's national grid of Tanzania Electricity Supply Company (TANESCO) does not guarantee access to power [10]. Those who are linked to the grid face an inconsistent power supply with frequent power outages and fluctuating supply. Off-grid renewable energy-based systems can be suitable for the provision of electricity in rural places [10]. TANESCO, a public utility company, owns and operates the country's power generation, transmission, and distribution infrastructure. Tanzania's current electrical generation mix includes hydropower, natural gas, and liquid fuel. For instance, in April 2018, the overall installed generation power capacity for the grid system was summed up to 1,435.56 MW (grid installed capacity is 1,351.1 MW, and off-grid plus imports is 84.46 MW), HPP (hydropower plants) accounts for 39.6% (567.7 MW), NGPP (natural gas power plants) accounts for 54.54% (782.82 MW), LFPP (liquid fuel power plants) account for 5.2% (70.54 MW), and BPP (biomass power plants) accounts for 0.7% (10.5 MW) [11]. Figure 1 indicates the electrical power generation mix in Tanzania. The figure indicates that electricity generation in the country by biomass has the lowest share. For the cross-border power supply, power capacities of 10 MW and 5 MW are purchased from Uganda and Zambia, respectively, and 1 MW is purchased from Kenya. IPP (independent power producers) account for 16.3% (205.36 MW) of total grid installed capacity [11].

The government of Tanzania has just started construction on the JNHPP (Julius Nyerere Hydropower Project), a 2,115 MW hydropower plant. It is also worth noting that some progress has recently been made. JNHPP construction is expected to boost installed capacity by more than 130 percent to roughly 3,700 MW [11, 12].

2.2. The Survey on the Hybridization of Solar and Biogas Energy Sources in Tanzania. In African countries including Tanzania, the level of generating electricity using renewable energy technologies is low [6]. Several studies indicate that power generation for rural electrification has been mainly focused on small electrical loads for residential, small commercial, and few institutional buildings without much consideration for productive uses of electricity [13]. Electrical load in these premises usually is supplied via single-sourced renewable energy systems and is commonly made for lighting, mobile phone charging, refrigeration, and entertainment. Single-sourced renewable energy systems are not reliable due to their intermittent nature, and therefore, there is a need for either energy storage systems which are expensive or hybrid technology. These systems provide useful social services in off-grid locations but with limited productive uses [14, 15]. For enhanced socioeconomic development in rural areas, small-scale industrial and street lighting loads need to be included in addition to residential, small-scale industry, commercial, and institutional loads [15]. This load includes small-scale welding enterprises, flour mills, small carpentry workshops, and small-scale sewing industries. The productive uses may also include other sectors such as agriculture, transport, and irrigation though in this work are neglected. Consequently, for improved reliability, cost-effectiveness, environmental benefits, and productive purposes, HRESS is a suitable choice [16]. In the SSA region and more specifically in Tanzania, there is a high potential for biomass in the form of animal wastes of which biogas can be tapped in for generating electricity via off-grid HRESS [17]. The huge potential could be helpful for the reduction of energy poverty in the region. Unfortunately, this potential from animal wastes remains unused. At the local level of the country and generally in the SSA nations, there are few studies on hybrid biogas-based electric systems [17]. This study tries to link the gap in the present literature. Additionally, the government of the United Republic of Tanzania via its research and development institutions supports the researches on the generation of electricity of such systems in the local sites with a substantial number of different livestock species. This kind of support from the government is a motivation for local researchers to work in this direction in investigating the potential of generating off-grid hybrid biogas-based energy systems [17, 18]. In the same view, this study is carried out to respond to such motivation from the government. The design of HRESS is mainly location-specific depending on local renewable energy resources and electrical load demand [19]. Based on the authors' observation and available literature, solar and battery systems hybridized with biogas generators are limited in the country. As a result, a solar PV-biogas-battery storage hybrid system is proposed. The system is anticipated to provide energy services to Simboya village located in Mbeya Rural District in Tanzania. The village does not receive any electricity from national central from TANESCO. This type of hybrid system is in research stages at different sites, and this particular research work contributes to the same track. Hence, prior to development and implementation, this system needs to be investigated to acquire knowledge about its potential and economic justification for the selected site and similar locations worldwide.

2.3. The Survey of Using RESs for Rural Electrification Worldwide: Gaps and Comparative Analysis. Numerous researches have been conducted along this track and trend. A large community of researchers has applied several simulation techniques and different approaches to investigate many kinds of renewable energy sources for electricity generation by conducting case studies of different places especially in isolated rural sites. Different places have also different availability of renewable energy resources, different potentials of renewable energy resources, and load patterns. This difference demands feasibility studies before the design and implementation of decentralized energy systems: Fleck and Hout compared two autonomous technologies, that is, small wind turbine system and single diesel generator-powered system. The wind turbine system is indicated to reduce significant greenhouse gas emissions in comparison with the diesel generator system [20]. Li and his fellow researchers carried out a feasibility study of hybrid technology for family houses in China. Hybrid technology consisted of wind, solar PV, and battery systems. A comparison among the technologies such as hybrid technology and two single sources of solar PV and wind turbine systems was made. The cost for solar PV with storage was found to be the highest followed by the wind turbine with storage, and hybrid solar-PV-battery storage was the cheapest [21]. Similarly, Rohan and Nour designed a hybrid renewable energy supply system for rural electrification in Abu Dhabi. Their study required an optimal arrangement of three sources of energy like diesel generators, solar PV, wind turbines, and battery storage equipment for the determination of power 0.5 MW. Optimization and simulation were implemented in HOMER software. Renewable sources were penetrated in the hybrid system approximately 45%, and the rest of the portion was made for diesel generators. Because of the high potential, wind resources had a better contribution than solar PV due to their high wind resource and less cost. Hybrid showed high least net present cost. High penetration of renewable energy sources is costly. In the same case, more than 30% of CO_2 emissions were decreased [21]. In developing countries, diesel-fueled power systems for a long time have been commonly used and are increasingly being substituted by or combined with nonconventional energy sources [22]. In addition, studies on solar PV-biogas-hybrid systems in SSA countries where Tanzania is also located have not been thoroughly analyzed [23]. Most of the HRESS-related researches are dominated by the combination of solar PV, wind, diesel, and batteries [24]. The amalgamation of solar PV and biogas power sources requires further extensive investigation as Tanzania's tropical climatic condition attracts the use of solar and biogas energy sources [6, 25]. Furthermore, the abundance of biomass and solar energy resources in the given site makes combining solar PV and biogas power sources apparent. The two sources can suitably complement each other for supplying reliable power supply in off-grid areas [25]. Yet, most of the researches do not provide the reliability, economic distance limit of grid network, and sensitivity analyses to find out its effect on the financial performance of the system [26]. Odoi-Yorke and coauthors carried out a feasibility analysis of solar PV/biogas/battery hybrid systems for rural electrification in Ghana using the HOMER platform. In the study, it was found that the system was better than the discrete DG or DG hybridized renewable energy-based system. In the analysis, LCOE was found to be \$0.256/kWh; the price is 64% higher than that of a domestic house [27]. Likewise, Zubair and his researcher designed a hybrid energy supply system in the coastal place of Bangladesh. The hybrid system consisted of wind-PV-DG hybrid systems. In the study, it was revealed that a hundred percent renewable energy-based supply system is not cost-effective. In the optimal group with the cheapest energy cost, 69% (55% and 14% for wind energy and solar PV, respectively) of total capacity represented renewable electricity, and the remaining percentage was power from DG. This system reduced CO_2 emissions by almost 70% compared to a single source generator [28]. In the same direction, Ngan and Tan investigated the possibility of implementing a hybrid energy system in Johor Bahru, Malaysia. This system included the technologies such as solar PV, wind turbine, and diesel generator. In the proposed site, solar energy resource has more potential than wind energy resource, and for that reason, solar PV has more penetration including DG. This hybrid PV-wind-DG system minimized CO_2 emissions by at least 35% [29]. Moreover, technoeconomic viability analysis of independent hybrid-PV-DG was performed by Ghasemi and his fellow researchers. The system was intended to supply electricity in one of the rural areas of Iran, and global solar radiation for Iran is sufficient for rural electrification at around 5 kilowatt-hour per metre square per day. The study showed that the DG system is not sustainable as it produces a large amount of GHG emissions [30]. Furthermore, Kusakana and Vermaak designed a hybrid PV-wind energy supply system and compared it in terms of cost of energy with only solar PV, only wind, and only DG. It was revealed that the hybrid system had the least cost of energy while the diesel generator indicated the highest cost of the same. The cost of energy of solar PV followed after hybrid then wind turbine technology, and DG had the highest cost of energy. The initial cost of the diesel generator is low, but the high cost of energy is due to its running cost [31]. Yahiaoui and his fellows carried out a case study for system sizing of a hybrid renewable energy supply system in Algeria. They used the grey wolf optimization technique opting for the algorithm in unit energy commitment data convergences. Ecological constraints and forthcoming load demand were neglected. The authors concluded that grey wolf optimization produced appropriate optimal sizing for the hybrid system and the hybrid configuration [32]. Ren and his friends made investigation on energy and ecological effects of the indirect exploitation of solar energy for dryer equipment. They used computer modelling techniques and TRNSYS software and described fundamental modelling calculations appropriate for optimization apparatus-based simulations [33]. Kaabeche et al. managed to give a solution for sizing optimization regarding a hybrid renewable energy supply system. They used a firefly-based algorithm which was compared with other artificial intelligence optimization techniques. It was found that the firefly-based technique was superior in terms of sizing solution among other optimization techniques. However, other parameters like environment impacts and load dispatch strategies were not included in this study [34]. Kabeel et al. explained optimal cooling equipment for enhancement of solar PV operation and cost-effectiveness in Egypt. System components used in modelling were based on the power supply generation in the country [35]. Ravinder and Bansal in 2019 analyzed the independent hybrid renewable energy supply system, and the same optimum configuration was recommended. They proposed a minimum index called final excess energy for optimal size configuration. This development of the algorithm activated the system within a limited time period [36]. Guimpayan established an optimal solution of microgrid operation for supplying power to the community via cooperative organizations. They used different optimization strategies for system component sizing like particle swarm optimization. It was concluded that HOMER software tools provide the best operational indicators for meeting the load demand of a given community [35]. Abu-hamdeh and Alnefaie analyzed the technoeconomic feasibility of four electrical power supply systems for several multiple buildings in Jeddah, Saudi Arabia. This study contained systems such as solar power tower, photovoltaic, wind turbine, and diesel generator systems and was intended to supply electrical power to small electrical loads. In this analysis, it was found that photovoltaic systems are the cheapest among the other options. It was also indicated that the initial cost of solar power tower systems was higher than the cost of solar PV at small loads. They expressed that the same system was cost-effective with large electrical loads. The cost of energy of DG was equivalent to that of solar power systems but was not a suitable option due to many shortcomings. The cost of energy systems for wind power systems was the highest because of the low potential of wind resources less than 3.0 m/s [37]. Murugaperumal and his fellow researcher performed feasibility design and technoeconomic analysis for supplying power in an isolated village of Korkadu, Puducherry region, India. The study was aimed at determining technical and economic feasibilities for the optimal configuration of a hybrid renewable energy supply system. It was observed that hybrid technologies can improve system reliability and minimize greenhouse gas emissions. They advised tapping the potential of biomass resources if available [38]. Bekele and Palm investigated the viability of supplying electrical power to the isolated public of two hundred families in Ethiopia. This investigation was based on a hybrid solar-wind energy supply system. Sigarchian et al. performed technoeconomic evaluation of a PV-wind-biogas hybrid system for providing electrical power supply to one of the villages in Kenya. It was observed that in terms of net present cost, cost of energy, and capital cost, the biogas power-generating machine was the best option for a backup system replacing the diesel engine. Energy share of 49%, 32%, and 19% represented power impact from solar PV, biogas engine, and wind turbine technology, respectively [39]. Anand et al. performed a feasibility analysis of a solar-biomass-based autonomous hybrid system for an isolated area in Sonipat, Haryana, India. This study was aimed at finding a suitable hybrid renewable energy supply system for the proposed hospital. The proposed model provided minimal cost and a significant reduction of GHG emissions [40]. Romero and Icaza proposed a photovoltaic/biomass/hydraulic hybrid system for the provision of electric power to the province of Bolivia, Ecuador. The objective of their study was to examine the support of local renewable energy resources to supply electricity in isolated areas of the country. In the study, it was found that the proposed HRESS has the potential to generate reliable power by employing batteries in the system [41]. Sen and his fellow researcher Bhattacharyya performed a feasibility analysis for generating electricity via a 100% hybrid RE-based system for Palari village, Bastar district, Chhattisgarh, India. The hybrid consists of RE sources such as solar, small hydro, wind energy, biodiesel generator as backup instead of DG, and batteries for maintaining fixed voltage in the absence of RESs. The authors of this paper concluded that the proposed system was cost-effective and environmentally friendly [14]. Rabetanetiarimanana et al. reviewed the measures taken for fostering the provision of electricity in rustic and isolated locations of the SSA region. Researchers presented the hurdles to the delivery of electricity to such sites. The authors also proposed renewable energy-based technologies particularly PV-hybrid systems which are less expensive as an alternative to commonly used DG systems. They also presented the appropriate methods for maximizing the utilization of renewable energy sources such as solar, small hydro, wind, concentrated solar power (CSP), and biomass, which can be used in the region. Also, the authors mentioned some planning tools which are applicable in the region including the widely used HOMER software. In their review, the authors concluded that the proposed renewable energy systems are more economically feasible than DG power stations [23]. Andrea et al. established economic models for supplying electricity through renewable energy-based minigrid systems in rustic areas of the SSA region. They established the model known as the KeyMaker Model which intends to reduce the aggregate of donations needed for supporting the preliminary investment and hence contributing to the viable development. The target of the model is to use the local minigrid electric systems to establish an agroprocessing scheme. They investigated the model of the 4 villages in Nigeria in order to investigate the potential of the model. HOMER software was used to simulate the systems for performing the economic feasibility analysis. The study indicated that without the proposed business model, economic donation requirements are higher lying in the range starting from 82 to 99% of the aggregate preliminary investment while with high quality of the same model, the donations reduce to 68%, 36%, 26%, and 8% for cocoa, maize, palm oil, and cassava, respectively. The authors concluded that the rate supplemented by introducing innovated local economic model reveals the decrease in donation requirements for rural electrification thus gaining socioeconomic benefits [42]. Diana et al. applied a multidisciplinary approach to developing a model for a load demand frame for expatriate camps, and they evaluated the implementation of unconventional energy systems. The study includes the technical-economic feasibility and challenges analyses specific to the refugee camp. The authors carried out modelling as a case study at a refugee camp located at Mantapala in Zambia. The authors simulated the systems using HOMER software and compared the alternative energy systems against the DG systems. One of the key findings of this study indicated that the implementation of hybrid renewable power systems is technically and financially feasible; costs for power fall up to 50% [43]. Trotter carried out a systematic review of energy planning and implementation in SSA. In their study, the author reviewed the quality and quantity of power planning and associated implementation research in each of SSA's 49 nations. This review indicated that 63% of related articles have favoured nonconventional power sources for the specified problems. Only 16% of the reviewed related theories advocate the use of hybrid energy systems. This review has mentioned that the HOMER platform is the most popular planning tool in SSA's states [44]. Zebra et al. conducted a review on the HRESS for an off-grid mini-grid system for providing electricity in developing countries. The concentration of the review was based on the experiences; technical, technological, and economic performance; and the major traits that can either obstruct or motivate the incorporation of these schemes in the less developed world. Off-grid HRESSs were examined and designed for considering the reliability due to the intermittency of renewable power sources. In the review article, the authors have stated the two main reasons for the success of the incorporation of HRESSs in developing counties, that is, received support from the government and community-based organization. Apart from other findings, this review shows that majority of Asian countries are more successful with minigrid systems. Similarly, Tanzania, for instance, is successful with the implementation of hydropower minigrids facilitated by REA. The LCOE of unlike minigrids has been compared, investigated, and compared. It has been observed by the comparison of LCOE of the technologies diesel, solar PV, and solar PV-DG hybrid. DG is the most expensive technology; its LCOE is in the range of \$0.92/kWh-\$1.30/kWh while solar PV technology is the cheapest technology, and its LCOE is in the range of \$0.40/kWh-\$0.61/kWh being cheaper than the hybrid. In addition, the authors presented the obstacles to the smooth implementation of minigrids including the absence of helpful policies and great investment costs. The findings are of specific significance for the less developed nations, where rural electrification through HRESSs is regularly faster and low-priced than grid power networks [22]. Keddar et al. investigated practical challenges which face the deployment of hybrid solar PV-diesel minigrid systems for electric cooking applications in the rural and isolated locations of Tanzania. They simulated the system using OpenDSS/MATLAB. The authors first investigate the limitations and constraints of the minigrid network in terms of the generation capacity available and different penetration levels. Generally, the findings have shown that voltage drop and disparity matters can be rationally and manageably advocated using conductors of greater size [45]. Bhattacharyya and Palit investigated critically and synthetically the literature on the off-grid–on-grid argument and discussed the rapport and the role between power generation preferences for expanding access to electricity in Asian and SSA nations. In the review article, the authors have explained that models which use larger resolution and capture low-voltage distribution networks seem to acclaim the distributed electric power solutions whereas the main power network appears as the favourite result of further accrued examination, focused population constellations, and greater demand circumstances. In addition, it has been indicated that the HOMER platform is majorly used for the technoeconomic viability analysis theoretically and not actual projects. In the review, the authors suggested the means of achieving widespread electrification, that is, strong governance and empowerment [46]. Kemausuor et al. conducted a review of the power planning tools and to what level the tools have been used in decentralized power systems in African states. The findings of this review article indicate that HOMER and Long-range Energy Alternatives Planning (LEAP) are the mostly used planning tools of renewable energy technologies. Other planning tools are RETScreen, network planner, MESSAGE, and MARKAL/TIMES. In particular, the study has mentioned power planning tools such as LEAP and MESSAGE to be used in Tanzania. Nigeria, Ghana, and South Africa are the nations with the greatest use of power planning tools. Conclusively, the review indicates that there is no any distinctive tool that might be fitting for all dissimilar power planning matters for the full deployment of renewable energy technologies [47]. Osman et al. carried out a feasibility study of integrating solar PV power sources into various available diesel-powered minigrid systems forming HRESS in Tanzania. They simulated and optimized the system using the HOMER platform at the lowest NPC and its corresponding LCOE. Based on these econometric metrics, a comparative study was made, with the solar PV-DG-battery bank being more cost-effective than discrete DG. Accrued NPCs for renewable-based systems and conventional energy systems are \$2,056,400 and \$1,726,922, respectively. Also, LCOEs for the solar PV hybrid and DG power station are \$0.35 and \$0.29/kWh, respectively. They concluded that the integration of solar PV into existing diesel power systems to form renewable energy-based hybrid systems is economically viable [48]. Creti et al. examined the managerial, tariff, and subsidy structures for minigrids in Mafinga in Mufindi district, United Republic of Tanzania. Also, the authors investigated the lucrativeness of electrification via a minigrid system project in private capital investment. Three technological alternatives were considered for the project such as DG, solar PV-battery, and HRESS. HOMER software was used for simulation and optimization purposes. The authors concluded that the legalised standardised SPP (small power producer) charges and funding schemes in the country still do not favour the minigrid system projects for the provision of electricity in rural areas due to high generation costs [49]. Hagumimana et al. carried out the technoeconomic examination of CSP and solar PV power sources in terms of strengths, weaknesses, opportunities, and threats (the SWOT approach). Later, the practical and financial viabilities of off-grid CSP and PV-based microgrid systems in Rwanda were implemented by the System Advisor Model (SAM). Results show that the off-grid solar PV-based microgrid system for the bucolic society is cheaper with the lowest NPC. Results of the SWOT approach and SAM model have indicated that both types of microgrids can have a great part in increasing access to electricity in the country. The authors intensely suggested the application of off-grid solar PV systems for providing utility-scale power in order to escalate access to electricity in Rwanda owing to their cost-effectiveness [50]. Khan et al. designed a new reliable and ecologically friendly solar PV-wind-hybrid system for a far-off location in the United Republic of Tanzania including CLC-SS (closed loop cooled-solar system). The system was optimized using HOMER software. In the design, the inclusion of CLC-SS enhanced the proficiency of the proposed HRESS by the extraction of extra energy from solar panels. The analysis of CLC-SS demonstrated a rise in energy output from ordinary solar panels by at least 10.23%. The findings authenticate that the optimized system has total NPC and LCOE of \$7,110.53 and \$0.26/kWh, respectively. The improved HRESS has been found to be economically viable [51]. Yusto established a model of HRESS consisting of anaerobic ingestion and solar and wind energy sources for energy generation in rustic semiarid locations particularly at Idifu village, Chamwino district, in Dodoma, Tanzania. One of the specific objectives was to simply carry out the technoeconomic evaluation of the proposed integrated energy system. An Artificial Neural Network (ANN) modelling method is beneficial for building biogas production forecasts of conventional HRESS using ANN models. Total NPC and LCOE were among the indices which were considered in the analysis. A comparative study between the conventional biogas system and innovated adapted batch fed anaerobic digestion (ABFAD) scheme was performed. At assumed discount rates of 9 and 12%, the actual LCOE was found to be TZS 1,312.71/kWh equivalent to €2017 0.57/kWh and TZS 1,464.63/kWh equivalent to €2017 0.64/kWh, respectively. The ABFAD presents the solutions to the functioning difficulties of ordinary anaerobic digestion systems, for instance, the easiness of reprocessing of leachate and small temperature deviation for achieving viable biogas production [52]. Bishoge et al. reviewed the potential of renewable energy resources for sustainable development in Tanzania. In their exploration, the authors identified, among other renewable energy technologies, the feasibility of generating electricity through biogas energy-based hybrid systems for rural areas, particularly in sites with a substantial amount of livestock. In this review, the authors mentioned the need for further investigation for harnessing effectively the potential of hybrid technology for commercial use [53]. Through simulation, Paul et al. investigated the possibility of integrating a solar-PV/battery system with DG. They identified off-grid DG power stations by the GIS-based approach and simulated this integrated system using the MATLAB simulation tool. They derived technical and economic solar PV and battery energy systems for hybrid minigrid systems. The authors developed a methodology for localizing the isolated DG minigrid systems. In their study, the authors also investigated the sensitivity of battery costs on storage capacity and renewable energy share. The authors concluded that the hybridization of DG-based off-grid systems with a solar PV/battery system can lead to considerable electricity cost reduction [54]. Khavari and Sahlberg carried out geospatial electricity demand and hybrid off-grid solutions to support electrification efforts in Tanzania using the Open Source Spatial Electrification Tool (OnSSET). They developed a method to consider hybrid electrification choices in geospatial electrification planning. In this study, a PV-diesel system was found cost-competitive economically with other minigrid technologies. In the same study, a wind-diesel system was found to be costlier [55]. Haji evaluated grid-connected and standby PV systems at the Karume Institute of Science and Technology (KIST), Zanzibar, and the Nelson Mandela African Institutions of Science and Technology (NM-AIST), Arusha, Tanzania. The study utilized the energy data from the two different locations. Current and voltages were acquired using the data loggers and power outputs as estimated. In addition, HOMER was used for simulation purposes. Simulation results indicate that the solar PV systems and grid power network at the KIST demonstrated saving approximately 40% of the accrued daily power consumption in comparison to grid connectivity. The LCOE was minimized starting from \$0.1877 to \$0.113. In another statement, the amalgamation of grid, solar PV, and battery systems at the NM-AIST showed an estimated saving of around 51% of daily power usage; the LCOE was minimized starting from \$0.22849 to \$0.113, respectively [56].

This specific research work tries to fill up the gaps as stated above by using both soft computing tools and AI optimization approaches. Furthermore, as portrayed in Figure 1, the share of biomass (including biogas) in electrical power generation mix is the least. In SSA countries including Tanzania, HOMER is extensively used in various studies with limited applications of AI optimization tools and hybrid biogas-based systems. So, in this study, a technical-economic analysis of the proposed off-grid HRESS for supplying electricity to the selected area of study has been performed using soft computing tools (Excel program and HOMER software) and AI optimization tools (GWO method). Similarly, the analysis involves the minimization of the total NPC and its corresponding LCOE of the off-grid HRESS in one of the rural areas of Mbeya region in Tanzania named "Simboya village." Technoeconomic viability analysis of HRESS in the first place has been executed using the HOMER platform and GWO technique.

2.4. Contributions of the Study. Based on the survey of the literature regarding the utilization of renewable energy resources for rural electrification at local and global levels, contributions of this research work are presented as follows:

(i) Hybrid biogas electric systems are limited in most developing countries particularly in the SSA region where the site under study is in the same location. Most of the available small energy systems in the region produce biogas for limited applications such as lighting, food preparation, and heating applications. Hence, this paper offers an optimization problem for novel designed optimal HRESS hybridizing solar PV and biogas energy sources to supply electricity in the rural areas

(ii) The paper presents the optimization of the system sizing using HOMER Pro software and a recently developed metaheuristic research platform called the grey wolf optimization (GWO) technique. Specifically, it includes the use of the GWO approach by considering system reliability

(iii) The study also offers a novel approach to sketching the graphs of NPC and LCOE in relation to break-even grid extension distance using linear equations

(iv) This study presents the economic comparative study of hybrid PV-BIOG-battery, PV-DG-battery, and DG systems versus break-even grid extension distance in the Tanzanian environment. Biogas generators are being considered to replace DG in hybrid solar PV-based systems. Also, the paper furthers the comparative analysis regarding GHG emissions between the abovenamed electricity generation options

(v) This paper offers awareness and enlightenment and fills the gap of missing energy data which are not available in most of the rural and remote areas of developing countries, including Tanzania, regarding the generation costs, performance, and use of hybrid biogas-based electricity systems

(vi) The paper provides the identification, exploration, and application of livestock-poultry biomass (biowastes) for the solution of energy deficiency and addresses the problem of environmental pollution (odour) due to animal and poultry wastes in the area of study

(vii) This study presents sensitivity analyses using HOMER Pro software and the GWO method

These energy deficits are considered important to exploring the potential complementarity, viability, and scope of all feasible infrastructures and solutions providing energy access. In this particular study, an off-grid HRESS incorporating equipment such as solar PV, biogas generator set, and batteries is proposed. In order to tap the advantage of a high sunlight source at the selected area of study located near the equator, the proposed model of hybrid energy systems includes solar PV panels. The utilization of solar PV technology is beneficial due to its modularity, negligible cost of operation and maintenance, simplicity in terms of installation, and environmental friendliness [57–60]. As a renewable energy source, solar radiation is intermittent leading to power output variability [57–60]. The intermittent nature of the solar energy source can be addressed by an introduction of an energy storage system particularly a bank of batteries and also by integrating complementary renewable energy sources or DG systems [57–60]. In other words, a practical amalgamation of solar with other renewable energy technologies integrated with DG or grid is deemed to be a technofinancially viable solution for rural power connectivity. However, DG systems are expensive and unclean, emitting GHG emissions, and insecure due to the depletion of fossil fuels and oil price volatility while main grid networks are far away from remote areas [57–59] [60, 61]. Therefore, off-grid renewable energy systems are compulsory for increasing access to electricity in rural areas. This study intends to maximize the potential of biogas fuel (form of biomass derived from animal manure anaerobically) in electricity generation mix of the Tanzanian power sector. In this study, solar PV is integrated with a biogas generator for improved efficiency, energy security, high reliability, reduced environmental negative impacts, and affordability in comparison with its DG counterpart [58, 60, 61]. Also, this study tries to address the challenge of scattered and random deposits of animal wastes and also mitigates environmental pollution from bad odour [58, 60]. Biogas fuel from biogas plants is injected to an internal combustion (IC) engine (modified diesel engines) to produce mechanical energy which is then converted into electricity by an electric generator. Apart from electricity generation and thermal production, agricultural gain can be maximized from biogas production thus increasing the income. In the proposed off-grid HRESS, batteries are also incorporated when solar radiation and biogas are unavailable. The integration of multiple energy sources of dissimilar characteristics is a complicated task requiring an extensive analysis. In this particular study, technoeconomic feasibility analysis of proposed off-grid HRESS is implemented. The analysis also involves applications of AI optimization techniques particularly GWO. The use of artificial intelligence solutions into power systems has the potential to significantly improve power efficiency, cost savings, and user comfort. As a result, developing intelligent optimization-based algorithms for application in various renewable energy systems is vital. In general, for achievement of widespread access to electricity, distinct policies for off-grid rural electrification have to be formulated [62]. Further research is required to analyze both the site-specific potential of RESs (renewable energy resources) and financial feasibilities of renewable energy resources (RESs) [62]. According to the preeminent knowledge of authors, no such research has been implemented previously at the selected area (Simboya village located at Ikukwa ward in Mbeya region, Tanzania). For that reason, this study tries to seal up this research gap. The overall contribution of this study is that it creates a roadmap for enhanced rural electrification at the selected area of study and other locations worldwide with similar conditions.

3. Methodology

3.1. General Description. Prior to the investigation of HRESS using HOMER Pro software, there are two important and significant aspects which are needed for any design of an electric system, i.e., availability of RESs plus their potential and estimated energy demand for the site of interest. Knowing the amount of energy of a particular place is helpful because it tells us the amount of energy to be generated. In this study, it is classified into residential, commercial, small-scale industrial, institutional, and street lighting loads. Agricultural and irrigation loads are neglected. The reason is that rural villagers of the area of study need not refrigeration for cooling agricultural products. Irrigation activities for the farms of the proposed site are carried out through the diversion of River Shongo and small streams of water flowing down under gravitational force from hills around Mt. Mbeya. This river supports lives and irrigation of Simboya and Ikukwa village. Electrical consumption for transportation is not applicable for this rural site. The components for HRESS are chosen in consonance with the availability potential of RES. The survey has been accomplished through site visitation, ward development records, extensive literature, interview, questionnaire, measurements, and internet surfing. All relevant data for required HRESS components, loads, RES, and prices are collected as input parameters in the optimization process in HOMER Pro software. HOMER is one of the analytical tools; its acronym stands for hybrid optimization of multiple energy resources. In the optimization, optimal configuration of HRESS is obtained for supplying sufficient electricity at minimum NPC (the life cycle cost, i.e., LCC), and apart from optimization, HOMER can perform sensitivity and GHG emission analyses. Figure 2 presents a comprehensive research approach.

Design of any hybrid system depends on the local renewable energy resources and load demand of a particular site. In line with the fieldwork that has been made at the area of study, there is a high potential of solar and biomass (animal waste and poultry droppings) energy resources, and thus, PV and biomass (biogas) generators have been used. Additionally, for a suitable performance, there is additional equipment such as power conditioning electronic devices, electrical load, and battery energy storage system. Normally, DG is used in HRESS as a backup to improve the performance of the system during maximum loads and absence of renewable energy resources. In this specific work, a biogas electric power generating unit is employed for backing up the system. This type of proposed HRESS is 100% renewable and therefore is cost-effective and environmentally benign. Figure 3 indicates a schematic arrangement of the off-grid HRESS for the proposed site. Based on the selected system components, optimal configuration is achieved via optimization. The grid has been included in the hybrid PV/biogas/battery bank storage only for economic comparison purposes and for this reason does not generate any power.

3.2. Description of Area of Study, System Design, and Energy Analysis. Simboya village is one of the two villages located at Ikukwa ward in Mbeya Rural District in Tanzania. Geographically, Simboya village is surrounded by mount Mbeya, Chunya district in Mbeya region, and Songwe region. Figure 4 indicates the map of the location of Simboya village at Ikukwa ward in Mbeya region, Tanzania. This village suffers from lack of access to electricity from national grid extension. Table 1 shows a summarized profile for Simboya village.

3.3. System Design and Energy Analysis

3.3.1. Solar Energy Resource. Monthly solar radiation and wind energy data were obtained from National Aeronautics and Space Administration (NASA) and Surface Meteorology and Solar Energy (SSE) [64]. The scaled annual average solar irradiance is 6.11 kWh/m^2/day at the proposed site. Table 1 shows the clearness index and monthly solar radiation data and wind speeds at the height of 10 m. Figure 4 indicates the monthly solar radiation and clearness index at the proposed site. Figure 5 shows detailed annual information of global solar radiation in Mbeya Rural District, Mbeya.

3.3.2. Biomass Energy. The following is the chemistry for producing biogas fuel during the anaerobic digestion process [65]:

$$\begin{aligned}\{\mathrm{C}_6 + \mathrm{H}_{12}0_6 \longrightarrow 3\mathrm{C}0_2 + 3\mathrm{CH}_4, \mathrm{CO}_2 + 4\mathrm{H}_2 > \mathrm{CH}_4 \\ + 2\mathrm{H}_2\mathrm{O}, \mathrm{CH}_3\mathrm{COOH} > \mathrm{CH}_4 + \mathrm{CO}_2\}\end{aligned} \tag{1}$$

Fuel consists of two main things such as methane (CH_4) and carbon dioxide (CO_2) representing about 55-65% and 35-45%, respectively. It also consists of tiny sulphide and gaseous form of water.

The simplified process of converting biomass obtained from animal and poultry wastes into biogas fuel for generation of electricity is portrayed in Figure 6.

This study focuses on evaluating potential for animal dung and poultry droppings at the village. Data collection regarding identification of types of animals and their quantification has been done through consultation of ward leaders and consultation of individual villagers and through records in the library of agriculture and livestock office in Ikukwa ward. Table 2 shows a list of livestock at Simboya village in Mbeya Rural District.

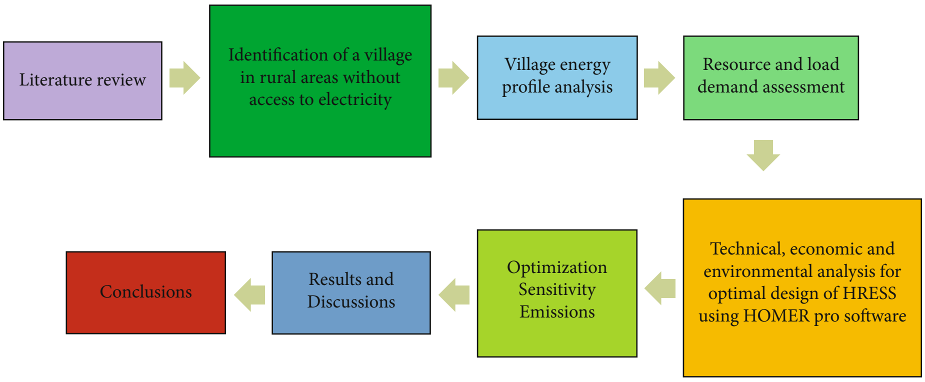

Figure 2: Comprehensive research approach.

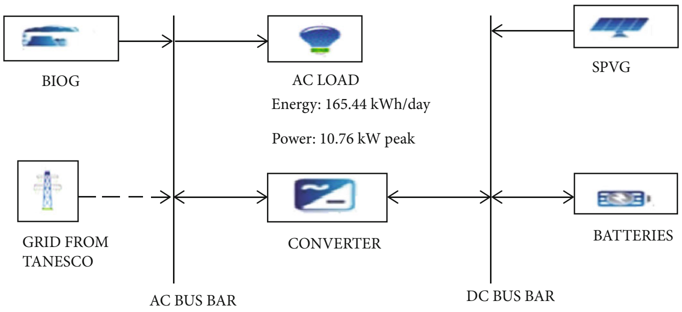

Figure 3: Schematic arrangement of the off-grid HRESS for the proposed site.

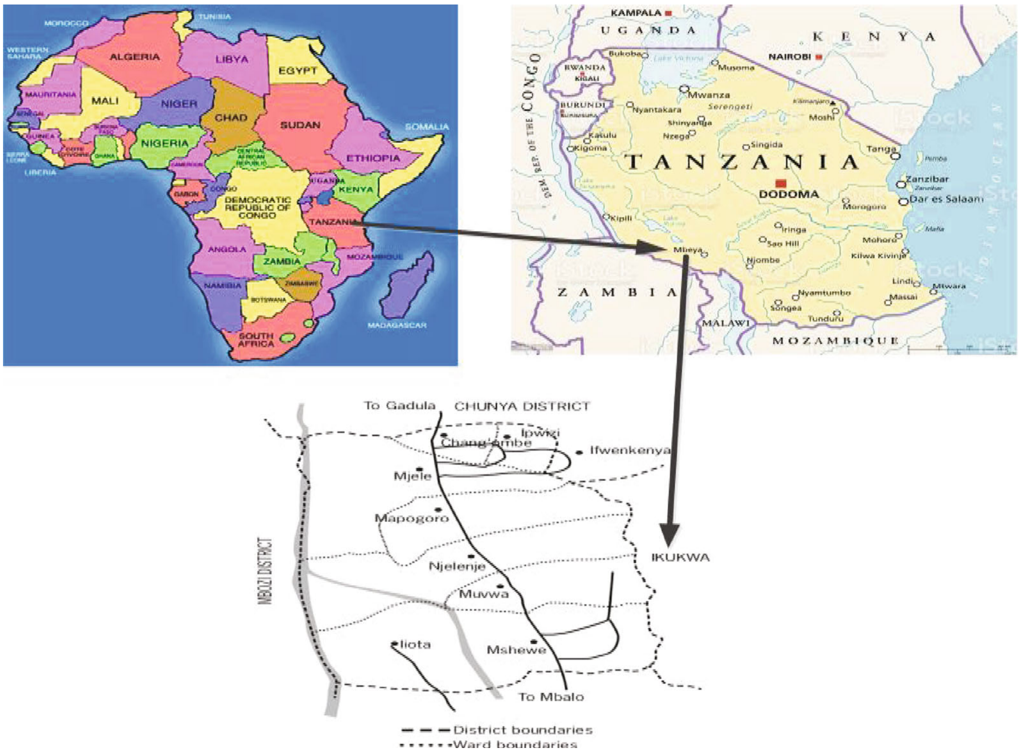

Figure 4: Map of location of Simboya village at Ikukwa ward in Mbeya, Tanzania (modified by authors: [63]).

Table 1: Summarized profile of the Simboya village.

Particulars	Description	Remarks
Name of the village	Simboya	—
Date of establishment	1998	Formed after subdivision of the former Ikukwa village established in 1964
Number of subvillages	09	Records from ward agricultural office
Number of residences	483	Records from ward agricultural office
Number of rivers	01	The river Shongo
Total area	5522 m^2	Data by Ikukwa ward office (WEO)
Total area for residences	3622 m^2	Data by Ikukwa ward office (WEO)
Agricultural area	700 m^2	Data by Ikukwa ward office (WEO)
Pastoralist area	1200 m^2	Data by Ikukwa ward office (WEO)
Total population	2536	Number of males: 1236 Number of females: 1300
Electricity availability	00	—
Ward name	Ikukwa	—
Name of the district	Mbeya rural	—
Name of the region	Mbeya	—
Latitude	8°54.6′S	—
Longitude	33°27.6′E	—
Country	United Republic of Tanzania	—

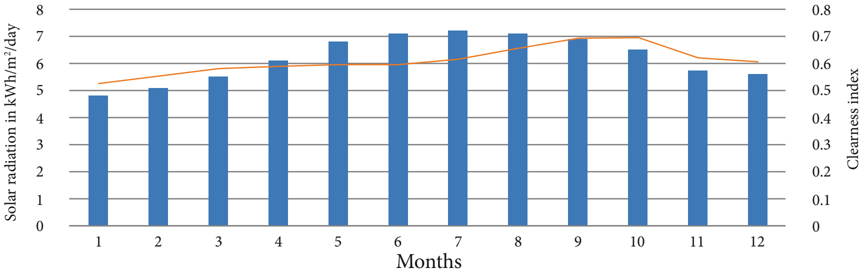

Figure 5: Synthesized monthly solar radiation and clearness index at the proposed site.

The quantity of dung produced per livestock per day differs depending on several factors like body size, kind of feeding, and amount of nutrition. For simplicity, production rates are approximated using the number of heads of surveyed herds in Simboya village, Mbeya Rural District, Tanzania. Table 3 indicates the yield of dung per head per day for Ikukwa ward in Mbeya Rural District.

The total amount of animal dung and poultry droppings is 10,365.9 kg/day. Firstly, gathering efficiency for animal waste is assumed to be 60%. And thus, the total amount collected per day is 60% multiplied by 10,491.8 kg/day which equals 6,295.08 kg/day. This amount is sufficient to produce biogas for electricity and cooking for the village households. An average of 2,040 kg/day out of the total daily biomass has been used for biogas electricity generation. The average price of biomass, low heating value (LHV), carbon content, and gasification ratio are \$3.0/ton, 5.5 MJ/kg, 5.0%, and 0.7, respectively. Secondly, it has also been observed that majority of animals and poultry in Africa are roaming from one place to another looking for pastures. The collection of biomass for biogas production may be a challenge. In this study, for an effective collection of animal dung and poultry droppings, zero grazing is assumed. Thirdly, the main source of feeding for the animals is assumed to be depending broadly on grass. The presence of grass is normally affected by the weather of the given place. It may now be implied that the amount of biomass collected during rainy seasons is higher than that in the dry season. In other words, the larger the amount of biomass, the higher the rate of feeding the animals, hence the high production of biomass per animal head. Based on these assumptions, the annual monthly average of available biomass resources is purposefully distributed over a period of one year. The highest and minimum produced annual monthly average biomass resources are in the month of January (0.787 tonnes/day equivalent to 12.5%) and in the duration starting from July to October (0.315 tonnes/day equivalent to 5% of total waste), respectively. In the period starting from March to April, daily available biomass is estimated to be 0.692 tonnes which is equivalent to 11%. Also, in November and December, the daily average weights of collected biomass are, respectively, 0.378 tonnes (6%) and 0.598 tonnes. Figure 7 indicates the annual

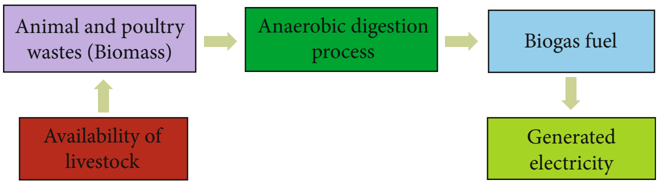

FIGURE 6: Simplified stages of electricity generation from biogas fuel.

TABLE 2: List of livestock at Simboya village in Mbeya Rural District.

Livestock	Cattle	Goats	Donkeys	Sheep	Pigs	Poultry
Total number	873	602	82	31	86	1448

TABLE 3: Assumed yield of dung per head per day for Simboya village in Mbeya Rural District.

Livestock	Assumed animal dung (kg/head/day)	Number of animals	Total dung (wet) (kg/day)
Cattle	10	873	8730
Goats	1	602	602
Donkeys	8	82	656
Sheep	1	31	31
Pigs	2.35	86	202.1
Poultry	0.10	1448	144.8
Total			10,365.9

monthly average available biomass resource for backup electricity generation. The daily generated power is given in the following equation [66]:

$$P_{\mathrm{BIOG}} = \frac{Q_{\mathrm{BIOG}\times}\mathrm{CV}_{\mathrm{BIOG}} \times \eta_{\mathrm{BIOG}}}{\left(T_{\mathrm{OPD}\times 860}\right)}, \tag{2}$$

where Q_{BIOG} denotes the amount of biogas (m^3/day), P_{BIOG} is the power generated by the biogas power plant (BPP) in kW, $\mathrm{CV}_{\mathrm{BIOG}}$ is the calorific value of biogas fuel (4,700 kcal/m^3), η_{BIOG} is the overall efficiency of BPP, and T_{OPD} is the operating time per day in hours. The remainder of the daily biomass resource equals 4,255.08 kg/day. In this study, 1 kg of dung is assumed to produce a daily amount of biogas of 0.036 m^3 [66]. As a result, total biogas production for cooking for all households in the village equals 0.036 m^3/kg times 4,255.08 kg/day which is estimated to be 153.2 m^3/day. The village comprises 483 families with a small amount of biogas for cooking per household which is equivalent to 0.32 m^3.

3.3.3. Classification of Electrical Load Demand. The approximated load demand has been obtained by the collection of information from the inhabitants and field surveys in the various sections of the village. These surveys are focused on a number of sections such as residential, institutional load, commercial, small-scale industrial, street lighting, irrigation, and agricultural loads. Data have been collected from the anticipated rated power of appliances depending on the type of electricity services. All sections consist of the lighting load. Residential loads consist of lighting, TV set, radio, DVD player, phone charger, and electric iron. Institutional loads consist of schools (primary and secondary), religious institutions, and community centres. Also, institutional loads include equipment of Mbeya District Council Hospital (MDCH), also known as Ikukwa Health Centre (IHC). The equipment for the hospital is used in sections such as morgue, laundry, image (X-ray and CT scan), administration building, theatre, maternity, premature babies services, clinic block, laboratory, minor surgery, pharmacy and store, injection room, dental room, staff households, security and street lighting, and miscellaneous sections. Commercial loads consist of small-scale shops, groceries, male saloons, and female saloons. Small-scale industrial load includes small carpentry workshops, sewing machines, milling machines, and welding machines. Street lighting load consists of security lights. Deferred load has been neglected as irrigation and agricultural activities do not need water pumping systems but electric power for transport. For an effective performance of the proposed off-grid HRESS, it is noteworthy to carefully take into account the electrical load profile. Any kind of periodic load variation can cause serious reliability problems in the system.

Based on the energy demand of each section, collected data from the surveys were intentionally spread over a 24-hour period on the Excel data sheet owing to the poor load factor in rural areas. The distribution of each load category was performed according to the engineering judgment reflected to time, social behavior, and nature of economic activities in the specified area of study. The daily load profiles for the whole village obtained by the Excel data sheet have been validated using the HOMER platform. Table 4 displays the electrical load categories in consideration of the consumer at Simboya village. The country's location is in a tropical region, and accordingly, the periodic variation of load based on winter and summer is not considered as there is not much variation in temperatures between the two seasons and thus no need for space heating/cooling equipment [67].

(1) Estimation of Electrical Load Demand at Pre-HOMER Level Using Excel Program. The assessment is carried out in the Microsoft Excel worksheet by customizing data

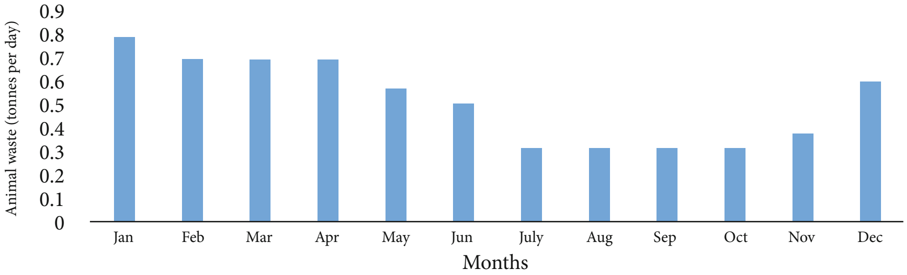

Figure 7: Annual monthly average available biomass resource.

templates before the detailed evaluation by HOMER Pro software [9]. Figure 8 indicates electrical load based on the considered applications for the area of study. The nature of graphs of power consumption is basically based on the behavior of socioeconomic activities of people dwelling in the area of study. The load classification above is further categorized as per consideration of the sensitiveness of health amenities. Here, sensitiveness means to ensure the constant availability and reliability of the health facility. The village electricity consumption is categorized into two main groups such as load profile 1 and load profile 2 [9]. In this study, load for IHC is excluded from institutional load and is combined with street lighting. For the efficiency and effectiveness of health centres, street lighting is of paramount importance. Therefore, load profile 1 (critical load) includes electrical load for the IHC and street lighting. Electrical load for IHC is constituted by a number of equipment of different rates of power consumption. In this specific study, due to the sensitiveness of IHC, its power consumption has been assumed to be constant throughout the day. Residential load is estimated to be 30 kW representing 50% of the daily maximum peak demand. Lighting load is the lowest at approximately 0.2 kW while power for transport and irrigated agriculture is zero. Load profile 2 (noncritical load) consists of residential, commercial, institutional, and small-scale industrial loads [9, 68]. Rural electrification projects based on commercial and small-scale industrial loads are limited to productive uses in the country. Figure 9 indicates critical loads which include the energy demand for the MDCH facility (also known as IHC) and street lighting load.

(2) Comprehensive Electrical Load Demand Analysis Using HOMER. Estimation of load profile in Excel data sheet is practically limited to peak power capacity. It is not capable of providing energy consumption per day, power variability, and load factor. Therefore, electrical load demand based on the existing types of consumers in the village is partially validated in HOMER Pro software in order to find the lowest cost amalgamation of supply choices by meeting the demand [9]. As has been aforementioned in this research, the HRESS is expected to generate electricity for the village (community) daily load of 165.44 kWh and peak power of 10.76 kW peak (scaled) or 63.41 kW (baseline) with a load factor of 0.64. Figure 2 is the schematic diagram for the HRESS for the proposed site. The considered HRESS is 100% renewable, meaning that no DG has been employed. Table 5 gives a summary of electrical power consumption for Simboya village per AC load classification processed in HOMER Pro software. In this study, the daily profile for IHC and its surrounding street lighting has been assumed to be constant all the time though there is a variation in power consumption. Figure 10 indicates daily power for noncritical loads (consisting of residential, institutional, commercial, and small-scale industrial loads).

Table 4: Electrical load categories in consideration of consumers at Simboya village.

Load classification	Wattage in watts collected from rating of electric appliances
Residential	465945
Institutional load including Ikukwa Health Centre	190730
Commercial	18121
Small-scale industrial	265338
Street lighting	4800
Irrigation and agricultural	0
Transport	0
Total	944934

4. Descriptions of Components and Design of Off-Grid HRESS

The survey carried out in the area of study has indicated that solar and biomass energy resources have a high potential of generating electricity. Therefore, electrical power-generating components in HRESS are solar photovoltaic (PV) panels and biomass/biogas generators (BIOG). In this study, BIOG is used as a standby. The devices such as deep cycle batteries and converters are also included in the system for energy storage and electrical power conversion, respectively.

Based on these selected components, optimal configuration is achieved from HOMER Pro software analysis. Figure 11 indicates the wiring scheme for the proposed off-grid hybrid solar PV-biogas-battery system for Simboya village, and Figure 12 shows the wiring scheme for the grid-connected hybrid solar PV-biogas-battery system for Simboya village.

However, in this study, grid connectivity of the grid-connected hybrid solar PV-biogas-battery system has been considered merely for economic comparison and examination of the economic distance limit (EDL) for the viable grid

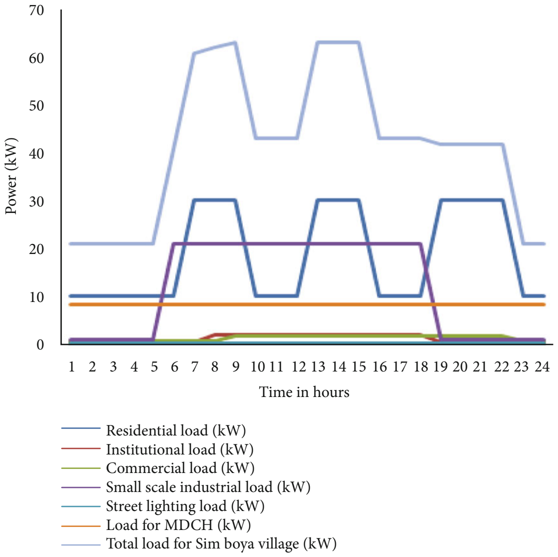

Figure 8: Accumulated load profile of various applications in the area of study.

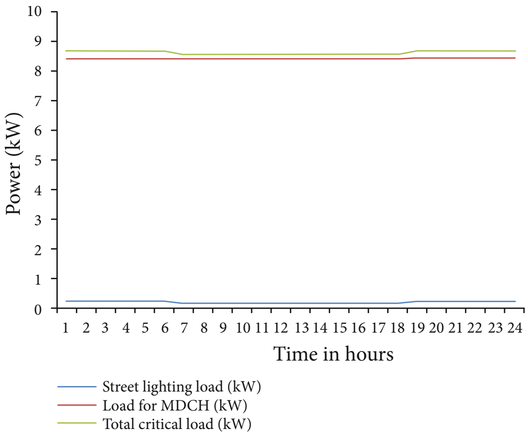

Figure 9: Critical load combining MCDH (IHC) and street lighting loads.

extension. The component's reliability and cost-effectiveness are important aspects of the successful micropower system design. The following is the selection of components and design of HRESS.

4.1. Selection of Components. A solar PV system consists of a number of panels in a series connection. Power output from PV constitutes a primary power in HRESS due to its cost-effectiveness compared with BIOG of equivalent capacity. Solar PV has been designed for generating a power output of 40 kW. The financial input parameters have been assumed in the optimization of the systems. The initial cost and replacement price for a capacity of 1 kW PV are considered $700.00 and $0, respectively. Performance of PV is assumed to be suitable within a timeframe of an anticipated project's lifespan of 25 years. Operation and maintenance (O&M) of PV are low, and it is only $1.5/year. The derating factor for the individual solar module is considered to be 80% in order to counteract the ambient temperature and unclean conditions. A PV system has no tracking system. Also, BIOG has been planned for delivering a power output of 25 kW. The initial price, replacement cost, and O&M price for a capacity of 1 kW BIOG are considered $260, $160, and $0.90/op.hr, respectively. BIOG is attached to AC output with a lifespan of 20,000 hours. The minimum load ratio is assumed to be 50% of the total power capacity. The bank of deep cycle batteries has been utilized to store excess power during the availability of high solar radiation and supply the stored energy to the electrical load in the absence of solar energy resources. The type of the selected battery is generic 1 kWh Li-ion with a nominal voltage of 6 V. The bank consists of 144 batteries, 4 batteries connected in series per string, and 36 strings in parallel, and the system bus voltage is 24. The initial price, replacement price, and O&M expenses per unit of the battery were taken as $700, $0, and $1.5/year. The battery bank has an autonomy of approximately 17 hours with a lifetime throughput of 432,000 kWh. The intended rated power output of the inverter is 40 kW. The initial price, replacement charge, and O&M expenses of the converter capacity for 1 kW were assumed as $200, $200, and $10, respectively. The lifespan of the converter is 15% while inverter and rectifier efficiencies are equal each with 95%.

4.2. Design of the Proposed HRESS. In this work, the design of the optimal solar photovoltaic-biogas-battery system was implemented in HOMER Pro software. Data for system configuration and selected components are used for the optimization process. Parameters such as capital price, cost of energy, and net present cost are obtained in the optimal design compared. Economic comparison is made in the financial section. There is a problem of uncertainty problem due to the intermittent nature of renewable energy sources (RESs). Uncertainties are related to the variability of the key input parameters of RES and thus lead to the complicated design of a microdistributed electric generating system. In this study, uncertainties have been considered, and therefore, variables such as solar radiation, fuel price, and load variation based on assumed scenarios (100% RE scenario) are a proposed primary scenario or base case scenario in which biogas is used as a backup; in the second scenario, DG is used as backup instead of biogas; and in the third scenario, DG is assumed to deliver power to the micropower system for continuous duty. The life cycle cost (LCC) method is used for financial comparison among the simulated feasible systems. The system which has the lowest NPC is the most economically favourable system, that is, optimally designed system. In this study, economics and constraints for the project are operating reserve which is 80%, nominal discount rate which is 8%, and expected inflation which is 4%. In this work, grid extension is used as a reference by HOMER for the comparison of both technical and financial parameters of the off-grid HRESS. Therefore, the specific objective of economic analysis between grid extensions versus off-grid HRESS is to examine whether the grid extension is viable or not. The critical price of grid extension per kilometre for the available terrain at Simboya village is considered to be

Table 5: Summary of electrical power consumption for Simboya village per AC load classification processed in HOMER Pro software.

Village load classification	Baseline max. power (kW)	Scaled consumption (kWh/day)	Scaled max. power (kW)	Load factor
Residential load	30.27	11.26	0.76	0.61
Institutional load	3.18	165.44	18.45	0.37
Commercial load	2.69	165.44	15.84	0.44
Small-scale industrial load	35.81	165.44	22.33	0.31
Ikukwa Health Centre (IHC)	8.42	165.44	6.89	1
Street lighting	0.42	165.44	14.94	0.46
Accumulated village load	63.41	165.44	10.76	0.64
Critical load	14.72	165.44	11.77	0.59
Noncritical load	54.84	165.44	11.82	0.58

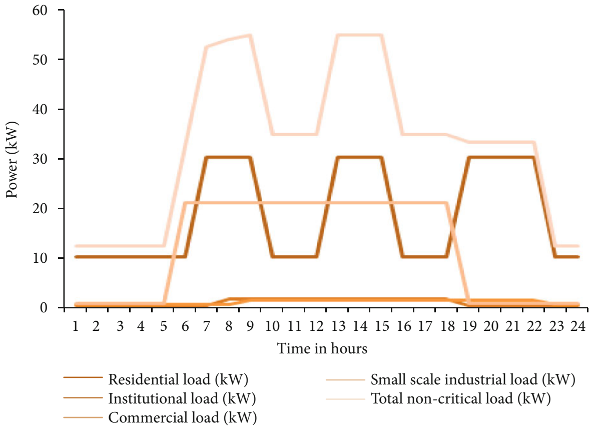

Figure 10: Noncritical load.

$8,000/km. The yearly O&M cost per kilometre is considered to be $1,500/year, and the grid power price in the Tanzanian environment is assumed to be $0.44/kWh. Based on LCOE and economic distance limit (EDL), a comparison of the economic effectiveness between the most favourable off-grid HRESS and grid extension for rural electrification is carried out. The price for the low voltage (LV) distribution systems in the village is not inclusive because the cost is similar in both options. Environmental analysis was also carried out to investigate the amount of emissions or pollutants in proportion to the selected components of the proposed off-grid HRESS.

5. Modelling of Amalgamated Power System Devices

It should be recalled that in this study, three off-grid optimal configurations, namely, solar PV-DG-battery, solar PV-biogas generator-battery, and DG-only systems have been compared. Out of the three optimized configurations, the solar PV-biogas generator-battery is the most cost-effective. Modelling of the individual components of the system is as follows.

5.1. Solar PV Generator. Solar power is generated based on the available solar energy resource at a given location. In this study, effects of temperature on solar cells are ignored. Therefore, the energy output of the solar PV generator (Gpv) can be computed using Equation (3) as follows [69]:

$$G_{\text{PV}}(t) = Q(t) \times A \times D \times \acute{\eta}_{\text{PV}}, \tag{3}$$

where $Q(t)$ represents the solar radiation (kWh/m^2), the surface area of the solar module (m^2) is denoted by A, D symbolizes the solar energy penetration factor, and $\acute{\eta}_{\text{PV}}$ denotes the efficiency of the solar PV generator (%).

5.2. Biogas Generator. In a biogas-powered generator, electricity is generated from biological wastes. Power generated by biogas is generally expressed in Equation (2). However, for the purpose of modelling, this equation can alternatively be expressed as follows in Equation (4) [70]:

$$P_{\text{BIOG}} = \eta_{\text{BIOG}} \times U_P(t) \times \text{CV}_{\text{BIOG}}, \tag{4}$$

where U_P(t) is the amount of biogas consumed (m^3/h), n_{BIOG} as an efficiency of biogas system (assuming it is equal to 27%), and CV_{BIOG} embodies the LHV (kWh/m^3). LHV relies on the concentration of CH_4 of the biogas. LHV is assumed to be 21.78 kJ/m^3 assuming the concentration of CH_4 is equal to 60%.

5.3. Battery Bank. In case energy generated by biogas and solar photovoltaic generators cannot satisfy the electrical load demand, the battery can start discharging in order to overcome such an imbalance. The battery capacity depends on SOC. The battery capacity of the system is defined in Equation (5) as follows [71]:

$$G_{\text{btt}\,(t)} = \frac{E \times DA}{V_{\text{btt}} \times \text{DOD} \times \eta_{\text{btt}}}, \tag{5}$$

where E denotes the daily energy demand (Wh), DA represents the number of days of battery bank autonomy, V_{btt} delineates system voltage, depth of discharge is abbreviated as DOD, and $_{\text{btt}}$ stands for battery efficiency. Quantity of batteries is prescribed based on ampere-hour capacity.

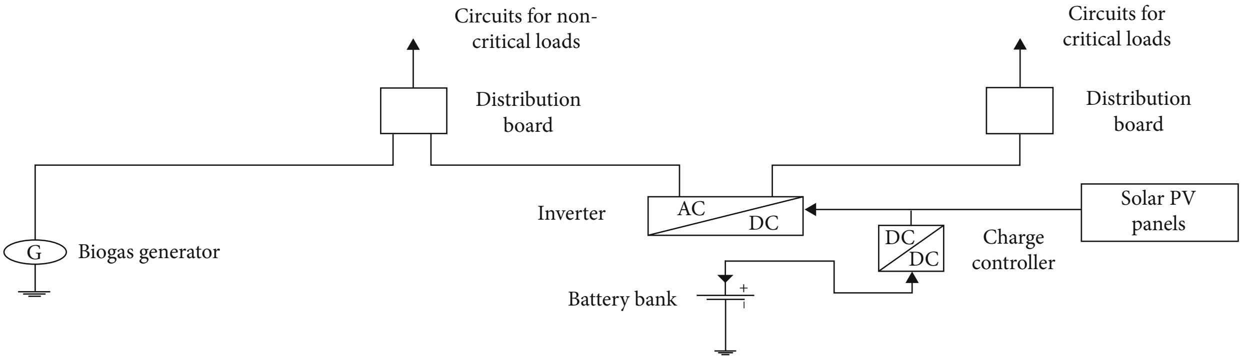

FIGURE 11: Schematic of the proposed off-grid hybrid solar PV-biogas-battery system.

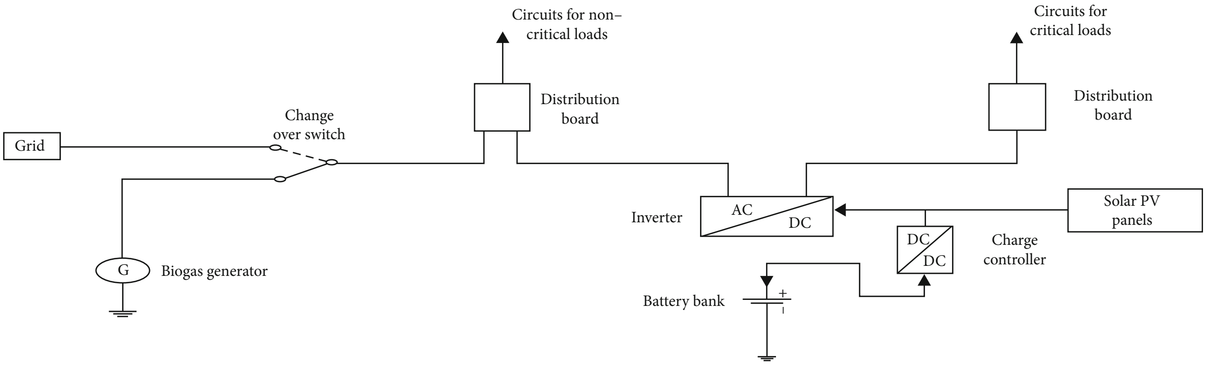

FIGURE 12: Schematic of grid-connected hybrid solar PV-biogas-battery system.

5.4. Converter. A converter is a bidirectional device combining an inverter and rectifier to maintain the direction of an electric current between the alternating current (AC) and direct current (DC) appliances. This device is necessary for smoothly interfacing energy sources, electrical load, and energy storage systems. The electrical load and biogas generator are connected to the AC bus bar while the solar photovoltaic array and battery bank system are connected to the DC bus bar. Converter power capacity should be at least greater than the highest load demand in order to permit the greatest rated power flow. Generally, input power to the inverter is computed using Equation (6) as follows [71]:

$$E_{\mathrm{INV}} = \frac{E_L}{\eta_{\mathrm{INV}}}, \tag{6}$$

where E_{INV} and η_{INV} define the input power and the efficiency of the inverter, respectively.

6. Economic and Technical Input Data of the Proposed Off-Grid HRESS

This section describes the financial and technical specifications including the details of the site of the project. In particular, the section presents the financial and technical specifications of the selected solar panel, biogas generator, battery, converter, description of the site of the project, and input parameters for solar panel, biogas generator, and converter, respectively.

6.1. Input Parameters of Solar PV Generator. In this study, the solar PV power system is considered to be fixed-mounted. The system is made by the connection of a number of solar panels so as to achieve the required values of system voltage and current flow. One type of PV panel is selected from Saatvik Green Energy Company with presumed costs for the Tanzanian environment [72]. Table 6 provides the input parameters of the solar PV module.

6.2. Input Parameters for Biogas Generator. The highest power to be produced by the biogas generator is anticipated to be 25 kW. Therefore, based on this fact, a unit of biogas generator from NPT General Exporters is considered, and all costs of the unit are adapted for the Tanzanian environment [73]. Table 7 shows the input parameters of the selected biogas generator.

6.3. Input Parameters of Battery. The intermittency nature is one of the drawbacks of renewable energy sources thus necessitating the use of energy storage systems like batteries. One type of battery is chosen from Shenzhen GSL Energy Company with presumed costs for the Tanzanian environment [74]. Table 8 provides the input parameters of the battery.

6.4. Converter. In this particular study, the capacity of the converter is assumed to be 20% higher than the estimated highest daily load demand. Converter experiences switching and conduction power losses [75]. Arithmetically, power capacity of invereter (E_{INV}) can be simply determined using

Table 6: Input parameters of solar PV module.

Parameter	Specifications
Manufacturer	Saatvik Green Energy Company
Model	SGE 335-72M
Rated power	335 Wp
Technology	Polycrystalline
Dimensions	1955 mm × 991 mm × 35 mm
Short-circuit current, I_{SC}	9.35 A
Open-circuit voltage, V_{OC}	46.25 V
Efficiency	17.29%
Capital cost	\$700
Operation and maintenance cost	\$1.5/year
Replacement cost	\$0
Lifespan	25

Equation (7) as follows:

$$E_{INV} = E_L + (20\%\text{of } E_L). \tag{7}$$

If load demand E_L equals to 63.41 kW is substituted into Equation (7), therefore estimated E_{INV} equals to 76.092 kW. Based on the available market, the inverter capacity of 80 kW is selected from Novergy Energy Solar Pvt Ltd [76]. Table 9 provides the input parameters of the converter.

6.5. Description of Connected Electrical Load. Electrical load is one or more appliances which are deliberately connected to an electric system to utilize electrical energy. For a proper design of any energy system for a given place, it is noteworthy to carefully consider the electrical load profile. Periodic variations of the electrical load need to be known for achieving a high-reliability system by maximization and minimization of power resources and costs, respectively. Moreover, the capacities of energy storage systems and energy sources rely on the electrical load profile. The data of load variation for the site under study are equal to 165.44 kWh/day and 63.41 kW.

6.6. Description of the Site of the Project. This section provides information related to the site such as lifespan, nominal discount rate, and inflation rate. Table 10 indicates the assumptions of input parameters of the site.

7. Strategy for Managing Off-Grid HRESS

Solar PV and biogas generators are the main sources constituting the hybrid energy system. Batteries are also incorporated into the system in order to compensate for the incompatibility between the energy demand and generated power.

Power generated by solar panels can be defined using Equation (8) as follows [77]:

$$G_{PV}(t) = n_{PV} \times p_{PV}(t), \tag{8}$$

where $G_{SP}(t)$ represents total power produced by solar photovoltaic array, n_{PV} refers to the quantity of solar panels, and p_{PV} (t) denotes power produced by one solar photovoltaic panel.

Table 7: Input parameters of biogas generator.

Parameter	Specifications
Company	NPT General Exporters
Model	KDGH25-G
Rated voltage	25 kW
Rated voltage	400 V/415 V/380 V
Frequency	50 Hz
Number of phases	Three phases (AC)
Power factor (lagging)	0.8
Engine model	HG4B
Speed	1500 RPM
Type of cooling	Natural cooling
Provision of power	Continuous
Capital cost	\$260
Operation and maintenance cost	\$0.9/year
Replacement cost	\$160
Lifespan	35

Similarly, power generated by a biogas generator can be defined using Equation (9) as follows [77]:

$$G_{BIOG}(t) = n_{BIOG} \times P_{BIOG}(t), \tag{9}$$

where $G_{BIOG}(t)$ represents the total power produced by all biogas power-generating units, n_{BIOG} refers to the quantity of biogas generators, and $p_{BIOG}(t)$ indicates power produced by a single biogas generator.

The total generated power obtained by the two sources is expressed by a combination of Equations (8) and (9) as follows [77]:

$$G_{SB}(t) = G_{PV}(t) + G_{BIOG}(t). \tag{10}$$

Alternatively, Equation (10) may be rewritten using Equation (11) as follows:

$$G_{SB}(t) = n_{PV} \times p_{PV}(t) + n_{BIOG} \times p_{BIOG}(t). \tag{11}$$

The produced power from the two renewable energy sources based on their obtainability is computed as follows [77]:

$$G_{SB}(t) = n_{PV} \times p_{pv} \times A_{pv} + n_{BIOG} \times p_{BIOG}(t). \tag{12}$$

The management strategy of renewable energy systems is complicated due to their discontinuous nature. In this study, the strategy consists of several setups that are explained as follows:

(i) *Setup 1.* Battery bank is allowed to charge only if the electrical load is met by all energy sources.

The battery bank is allowed to charge when power generated by the energy system is greater than the energy

Table 8: Input parameters of battery.

Parameter	Specifications
Manufacturer	Shenzhen GSL Energy Company
Model	KS-12300
Nominal voltage	12 V
Nominal capacity	300 AH
Type	Lithium-ion battery ($LiFePO_4$ battery)
Cycle life	More than 3000 times
Efficiency η_{btt} (assumed)	85
DOD (assumed)	80
Lowest permissible charge	20
Capital cost	\$700
Operation and maintenance cost	\$10/year
Replacement cost	\$700
Lifespan	10

Table 9: Input parameters of converter.

Parameter	Specifications
Manufacturer	Novergy Energy Solar Pvt Ltd
Model	IPCL 80 kW
Type	Hybrid (on-grid/off-grid)
Rated output voltage	380 V/400 V/415 V AC, TPN
Rated power capacity	50 Hz
Rated power capacity	80 kW
Power factor	0.8 lagging
Efficiency η_{INV}	92%
Capital cost	\$200
Operation and maintenance cost	\$10/year
Replacement cost	\$200
Lifespan	10

Table 10: Assumptions of input parameters of the site.

Parameters of the project	Specifications
Lifespan	25 years
Nominal discount rate	8%
Expected inflation rate	4%

demand at a given time. The battery bank is charged to store the surplus energy when the load is satisfied first. Energy stored by the battery bank is expressed in Equation (13) as follows [78]:

$$G_{\text{btt}\,(t)} = G_{\text{btt}\,(t-1)} + \left(G_{\text{SB}(t)} - \frac{E_L\,(t)}{\eta_{\text{ivt}}} \right) * \eta_{\text{btt}}, \qquad (13)$$

where $G_{\text{btt}\,(t)}$ and $G_{\text{btt}(t-1)}$ are defined as electrical energies stored in the battery bank at t and $t-1$ times, respectively; $G_{\text{SB}(t)}$ represents energy produced by the hybridized energy system; $_{\text{btt}}$ and $_{\text{ivt}}$ represent efficiencies for battery and inverter, respectively; and energy demand at time t is symbolized by$E_L(t)$.

(ii) *Setup 2*. Battery discharges only if the electrical load is not met by all energy sources.

The battery bank is required to discharge if power generated by the energy system is lower than the energy demand at given time t. Therefore, the energy from the battery bank is discharged to meet the load. Energy discharged by the battery bank is described in Equation (14) as follows [78]:

$$G_{\text{btt}\,(t)} = G_{\text{btt}\,(t-1)} - \left(\frac{E_L(t)}{\eta_{\text{ivt}}} \right) - G_{\text{SB}\,(t)} \Bigg). \qquad (14)$$

(iii) *Setup 3*. Otherwise, the load is not met by energy sources and battery storage system meaning that there is a deficiency of energy. This idea is fully discussed in relation to system reliability [78].

8. Optimization of Off-Grid HRESS Using GWO Method

The first phase of this paper has been executed in HOMER Pro software. This software mimics the probable system configurations to acquire the optimal arrangement of hybridized energy sources to meet the daily load demand. Input data related to solar radiation, biomass particularly animal and poultry wastes, components of the system, and load demand have been used for the simulation process. In the second phase, application of the GWO method is employed. In this particular phase, LEPP, NPC, and COE are minimized. These parameters are known as objective functions. Decision variables are rated power output of solar PV, number of biogas generator, autonomy days of battery system, and number of DG. In short, this section deals with financial and technical optimization models as follows.

8.1. Technical Optimization Model. This section of the paper offers a detailed explanation of the reliability of the system in relation to setup 3 of the management strategy. LEPP defines the reliability factor of a microgrid system. A reliable energy system can meet the load sufficiently for a given period of time. On the other hand, the less the LEPP, the more the system is reliable. LEPP denotes a reliability factor of the microgrid system. If the value of LEPP is equal to zero, it means that power generated and load demand are perfectly balanced. If the same factor is equal to one, it implies that there is an imbalance of power generated and load demand due to the shortage of electricity. Therefore, before defining LEPP mathematically, the deficiency of electricity called unavailability of electricity supply (UES) is expressed in Equation (15) as follows [78]:

$$\mathrm{UES}_{(t)} = E_{L(t)} - \left(G_{\mathrm{PV}}(t) + P_{\mathrm{BIOG}}(t) + G_{btt\,(t-1)} - G_{bttMIN}\right) * \eta_{ivt}. \tag{15}$$

Now, LEPP for duration of time T can be defined as a ratio of the whole UES calculated every period t to the sum of power demand. The ratio is mathematically described in Equation (16) as follows [71, 77, 78]:

$$\mathrm{LEPP} = \frac{\sum_{t=1}^{T} \mathrm{UES}_{(t)}}{\sum_{t=1}^{T} E_{L(t)}}. \tag{16}$$

Renewable fraction (RF) is defined as a fraction of power delivered to the load which is generated by nonconventional energy sources. Numerically, REF is expressed using Equation (17) as follows [71]:

$$\mathrm{RF} = 1 - \frac{\sum_{t=1}^{8760} \mathrm{out}_{DG(t)}}{\sum_{t=1}^{8760} G_{SB}(t)}. \tag{17}$$

$\mathrm{out}_{DG(t)}$ connotes the power generated by conventional energy sources (solar PV and biogas). In this study, the system consists of 100% nonconventional energy sources, and thus, RF equals 1.

8.2. Financial Optimization Model. It should be recalled that in the first part of this study, the HOMER platform has been used to simulate the system. The central function of the tool is to obtain optimal configuration at the smallest total NPC [79]. This platform of research calculates the mean annualized price of each system component plus associated penalties of ecological pollution [72]. This type of price is useful for determining the total NPC and LCOE [79]. Both economic metrics can be generated using the annualized capital cost of every component of off-grid HRESS. In the second phase of this study, optimization is implemented by using the AI approach using the GWO method, and the particular economic index used is the least total NPC. The following is the description of the economic index.

8.2.1. Computation of Total NPC. One of the primary parameters for establishing the sustainability of off-grid HRESS is the total NPC. The NPC can be simply defined as a sum of the whole expenses of the project's lifespan in Equation (18) [80]:

$$\mathrm{NPC} = \frac{\mathrm{AAP}}{\mathrm{CRF}\left(i, J_{\mathrm{proj}}\right)}, \tag{18}$$

where J_{proj} is the lifespan of the project in years and CRF represents the capital recovery factor in Equation (19) [79, 80]:

$$\mathrm{CRF}\left(i, J_{\mathrm{proj}}\right) = \frac{i(1+i)^{J_{\mathrm{proj}}}}{\left((1+i)^{J_{\mathrm{proj}}} - 1\right)}, \tag{19}$$

where CRF is defined as the capital recovery factor, i is the nominal discount rate, and J is the lifespan of the proposed HRESS with battery energy storage.

8.2.2. Computation of Aggregated Annualized Price. Aggregated annualized price (AAP) includes the whole annualized prices of the system in \$/year. It consists of annualized investment price (AIP), annualized spare price (ASP), annualized fuel price (AFP) of energy source, and annualized operation and repair price (AOMP) of the hybrid system. AAP can be determined using Equation (20) as follows [69]:

$$\begin{aligned} \mathrm{AAP} = {} & \mathrm{AIC}\,(\mathrm{PV} + \mathrm{BIOG} + \mathrm{Battery} + \mathrm{Converter}) \\ & + \mathrm{ASP}\,(\mathrm{PV} + \mathrm{BIOG} + \mathrm{Battery} + \mathrm{Converter}) \\ & + \mathrm{AFP}\,(\mathrm{PV} + \mathrm{BIOG}) + \mathrm{AOMP} \\ & \cdot (\mathrm{PV} + \mathrm{BIOG} + \mathrm{Battery} + \mathrm{Converter}). \end{aligned} \tag{20}$$

AFP of the solar energy source is ignored because the fuel is free of charge. Furthermore, the total NPC of solar PV is further reduced due to its lifespan of 25 years equivalent to the project life cycle. AOMP of fixed solar PV are trivial and thus negligible. Unavailability of AFP, AOMP, and ASP of solar PV is beneficial because, for a given lifespan of 25, the total NPC is significantly reduced. The total NPC of other individual components such as the battery and converter is increased over the whole lifespan due to the requirement of AOMP depending on the lifespan of every component. AFP of BIOG is taken into account as biogas fuel is sold at 80% of diesel fuel cost. In addition, for a simplified analysis of the system, salvage value is neglected.

8.2.3. Computation of LCOE. LCOE (\$/kWh) refers to the average charge per unit of useful generated electricity. LCOE can be computed in Equation (21) as follows [79, 80]:

$$\mathrm{LCOE} = \frac{\mathrm{NPC} \times \mathrm{CRF}}{\text{Energy produced per annum (kWh/year)}}, \tag{21}$$

where EL is the total annual energy consumption (kWh/year). LCOE may alternatively be computed in terms of AAP using Equation (22) as follows [79, 80]:

$$\mathrm{LCOE} = \frac{\mathrm{AAP}\ (\$/\text{year})}{\text{Energy produced per annum (kWh/year)}}. \tag{22}$$

8.2.4. Formulating Objective Function and Constraints. One objective optimization technique with a focus on the total NPC standards and its corresponding LCOE is employed. The research platform deployed in the entire optimization process for coding is MATLAB. The principal goal is the minimization of the total NPC. Here, total NPC represents the suitability function subject to several limits (constraints). The decision parameters are area of solar PV module (A_{PV}), power generated by biogas generator (P_{BIOG}), quantity of batteries (N_{btt}), and quantity of converters (N_{CONV}). The objective function is formulated under the constraints of decision parameters, and system reliability is presented in Equation (23) as follows [69]:

(1) Objective function

$$\text{Minimization of total NPC} = \sum_{i=A_{\mathrm{PV}},P_{\mathrm{BIOG}},N_{\mathrm{btt}},N_{\mathrm{CONV}}} \left(\frac{\mathrm{APP}_i}{\mathrm{CRF}}\right) \tag{23}$$

(2) Constraints

$0 \le A_{\mathrm{PV}} \le A_{\mathrm{PV}}^{mx}$, $0 \le p_{\mathrm{BIOG}} \le P_{\mathrm{BIOG}}^{mx}$, $0 \le N_{\mathrm{btt}} \le N_{\mathrm{btt}}^{mx}$, $0 \le N_{\mathrm{CONV}} \le N_{\mathrm{CONV}}^{mx}$, and $0 \le \mathrm{LEPP} \le \mathrm{LEPP}^{mx}$

N_{btt} and N_{CONV} are integers; A_{PV}^{mx}, P_{BIOG}^{mx}, N_{btt}^{mx}, N_{CONV}^{mx}, and LEPP^{mx} are the greatest values of the total area of solar modules, generated power by biogas power generating unit, quantity of batteries, quantity of converter, and system reliability index, respectively. In this phase of the study, the GWO method is used to evaluate the objective function under the specified constraints. Based on the selected sizes of components of the system within their defined constrained limits, the viable configurations are found at the least total NPC in the light of the prescribed values of LEPP of the HRESS.

8.2.5. Application of GWO Method. The GWO method was devised by Mirjalili and his coresearchers in 2014 [69] [81]. In accordance with the researchers, this method is motivated by the social headship pyramid and mechanism of hunting grey wolves in nature. The commanding chain of the wolves is split up into four groups such as alpha (α), beta (β), delta (δ), and omega (ω) without taking into account gender. In the GWO method, the finest solutions are denoted by α, followed by β and δ wolves [69, 81]. ω is the final group (scapegoats) which is submissive to the dominant groups (α, β, and δ). The whole process of hunting is assumed to be executed by the dominant groups [69]. The procedure of hunting is implemented in three phases such as tracing which involves chasing and moving near the target, following the victim, and attacking the victim [69, 81]. A numerical model is formulated referring to the aforementioned phases of hunting. In the first place, the encircling manner is numerically modelled using Equations (24) and (25) as follows [69, 81]:

$$\vec{C} = \overrightarrow{\mu_2} \cdot \overrightarrow{L_p}(i) - \overrightarrow{L_g}(i), \tag{24}$$

$$\overrightarrow{L_g}(i+1) = \overrightarrow{L_p}(i) - \overrightarrow{\mu_1} \cdot \vec{C}. \tag{25}$$

$\overrightarrow{\mu_1}$ and $\overrightarrow{\mu_2}$ in the above equations represent the coefficient vectors of the targeted victim. These vectors are computed using Equations (26) and (27) as follows [69, 81]:

$$\overrightarrow{\mu_1} = 2 \times \vec{A} \cdot \overrightarrow{R_1} - \vec{A}, \tag{26}$$

$$\overrightarrow{\mu_2} = 2 \cdot \overrightarrow{R_2}, \tag{27}$$

where $\overrightarrow{L_g}(i)$ and $\overrightarrow{L_p}(i)$ stand for the location of the wolves and the victim in the ith iteration. Magnitudes of $\vec{A}$ diminish linearly starting from 2 to 0 in the course of iteration. $\overrightarrow{R_1}$,$\overrightarrow{R_2}$ represent arbitrary vectors in the range of 0 to 1. As has been explained before, the process of surrounding the victim is headed by β and δ. After the accomplishment of the encircling, another phase of finalizing the process is implemented by the leading group of grey wolves from their respective locations. This final stage is mathematically expressed in Equations (28), (31), and (34) as follows [69, 81]:

$$\overrightarrow{C_\alpha} = \left|\overrightarrow{\mu_2}[1] \times \overrightarrow{L_\alpha} - \overrightarrow{L_p}\right|, \tag{28}$$

$$\overrightarrow{C_\beta} = \left|\overrightarrow{\mu_2}[2] \times \overrightarrow{L_\beta} - \overrightarrow{L_p}\right|, \tag{29}$$

$$\overrightarrow{C_\delta} = \left|\overrightarrow{\mu_2}[3] \times \overrightarrow{L_\delta} - \overrightarrow{L_p}\right|, \tag{30}$$

$$\overrightarrow{L_p}[1] = \overrightarrow{L_\alpha} - \overrightarrow{\mu_1}[1] \times \overrightarrow{C_\alpha}, \tag{31}$$

$$\overrightarrow{L_p}[2] = \overrightarrow{L_\beta} - \overrightarrow{\mu_1}[2] \times \overrightarrow{C_\beta}, \tag{32}$$

$$\overrightarrow{L_p}[3] = \overrightarrow{L_\delta} - \overrightarrow{\mu_1}[3] \times \overrightarrow{C_\delta}, \tag{33}$$

$$\overrightarrow{L_p}(i+t) = \frac{\overrightarrow{L_\alpha}[1] + \overrightarrow{L_\beta}[2] + \overrightarrow{L_\delta}[3]}{3}. \tag{34}$$

$\overrightarrow{\mu_1}$ denotes an arbitrary value that lies in the range from $-2A$ to $2A$. If $|\mu_1|$ is lower than 1, grey wolves are required to attack the victim. If $|\mu_1|$ is larger than 1, grey wolves are compelled to go away from the victim.

8.2.6. Execution of GWO Method for Optimal System Sizing. The following are the important steps of executing the GWO method for optimal system sizing [77, 81]:

(i) Preparing the magnitude of the population and input variables of GWO

(ii) Establishing the search representative and producing the parameters arbitrarily (selecting randomly the quantity of solar PV modules and biogas power generating units from relevant constraints)

(iii) Estimating the number of batteries after the computation of the total produced energy by renewable energy sources of the system by taking into account the reliability (obtaining the feasible population subject to the predefined LEPP value from relevant constraints)

(iv) Feeding the decision variables to the formulated objective function (Equation (23)) from the set of feasible population and calculating total NPC

(v) Selecting the least total NPC acquired from the feasible populations equal to the population size. The

NPC is assumed as the finest fitness for the first iteration

(vi) Updating the location of exploration agents, while $t <$ the greatest sum of repetitions and randomly compute the amount of solar PV modules

(vii) Computing the formulated objective function of new exploration agents by estimating the quantity of batteries

(viii) Determining the new finest exploration agents and substituting it with the old finest exploration agent, knowing that the new is superior to the old finest exploration agent

(ix) Is the terminating condition fulfilled? If it is not, repeat step (ii), and if the condition is satisfied, then move to the next step

(x) Determining the optimal size (optimal parameters including the least value of LCOE) of the proposed energy system and finalizing the GWO method

Two main conditions have been used during the modelling strategy to consider for LEPP evaluation with respect to the energy demand in the entire process of optimization:

Condition 1. When solar PV panel is generating surplus power in comparison with authentic energy demand.

Condition 2. When solar PV panel is generating less power in comparison with authentic energy demand.

9. System Reliability and Sensitivity Analysis Using GWO Algorithm

Prior to carrying out the sensitivity analysis, technoeconomic analysis of off-grid HRESS is carried out using the GWO method in addition to HOMER software. In this first case, the system is assumed to be balanced meaning that generated power supply and load demand are balanced. In such a condition, there is no shortage of energy. However, this condition practically cannot always be maintained as generated power varies periodically. In the second case, the analysis of the system is further investigated by the variation of LEPPs. Here, the designed system is assumed to generate power less than the generation power capacity. In this context, generated power supply and energy demand are not balanced implying a shortage of power. This section of the research article presents system optimization and sensitivity analysis.

9.1. The Uppermost and Lowermost of LEPP. LEPP can be computed using Equation (16) after the determination of the shortage of power supply using Equation (15). For the straightforwardness of calculating the LEPP, in this study, Equation (4) can be simplified into Equation (35) as follows [77, 78]:

$$\mathrm{UES}_{(t)} = E_{L(t)} - \left(G_{\mathrm{SB}}(t) + G_{\mathrm{btt\,bank}\,(t)}\right). \tag{35}$$

Table 11: Miscellaneous specifications for GWO technique.

Parameters	Value
Population size of grey wolves, n	12
Maximum number of iterations, $\mathrm{iter}_{\max}$	100
Inflation rate	6%
Interest rate	3.04%
Highest capacity of biogas generator, $P_{\mathrm{BIOG}}^{\mathrm{maxi}}$	25 kW
Highest quantity of solar panels, $N_{\mathrm{PV}}^{\mathrm{maxi}}$	100
Highest quantity of batteries, $N_{\mathrm{btt}}^{\mathrm{maxi}}$	764
Highest quantity of converters, $N_{\mathrm{CONV}}^{\mathrm{maxi}}$	20
Highest LEPP, $\mathrm{LEPP}^{\mathrm{maxi}}$	0.07

If power generated from renewable energy sources plus stored power in the battery bank satisfies all energy required for 100%, Equation (35) is rewritten as Equation (36). LEPP can be estimated using Equation (16) as follows [77]:

$$\mathrm{UES}_{(t)} = E_{L(t)} - 100\% * E_{L(t)}, \tag{36}$$

$$\mathrm{UES}_{(t)} = 0. \tag{37}$$

Using the GWO method, an appraisal of the objective function consistent with the delineated constraints is made. Sizes of components are selected within the stated limits. Identification of viable configurations of the hybrid system is done in relation to the preset magnitudes of LEPP. The best possible solutions are repeated in the GWO method. The structure is updated to estimate the minimum total NPC. LEPP is determined by substituting Equation (36) into Equation (16) which equals zero. It implies that the system satisfies the power supply requirement when $\mathrm{LEPP} = 0$. Also, the system is also assumed to produce power not lower than 93% of the whole load giving the highest value of LEPP equal to 0.07. Values of LEPP for the sensitivity analysis are evaluated with a similar approach. Here, the hybrid energy system is assumed to generate power of 96% and 94% of the total actual load yielding LEPP values equal to 0.04 and 0.06, respectively. Table 11 specifies miscellaneous specifications for the GWO technique.

9.2. Comprehensive Methodology for Sizing the Proposed HRESS Using GWO Algorithm. Optimization parameters such as solar radiation, animal wastes, and electrical load data and assumed constants (data sheet) were used as input variables. Decision variables like A_{PV} and P_{BIOG} were estimated by the GWO algorithm for individual iteration. Then, the power from solar PV (P_{PV}) and biogas generator (P_{BIOG}) were estimated with variable inputs, assumed constant inputs, and approximated decision variables. In order to meet the energy requirements, the potential of solar energy is considered to be maximized deliberately so as to use an advantage of free fuel in comparison with biomass, in this case, animal wastes. However, if generated electricity from aforesaid energy sources does not satisfy the load demand, stored energy from batteries is used to balance power supply

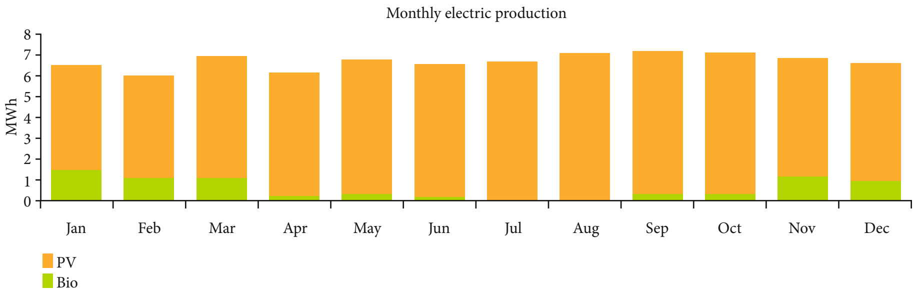

FIGURE 13: Annual monthly electric production of hybrid PV-BIOG-battery storage system.

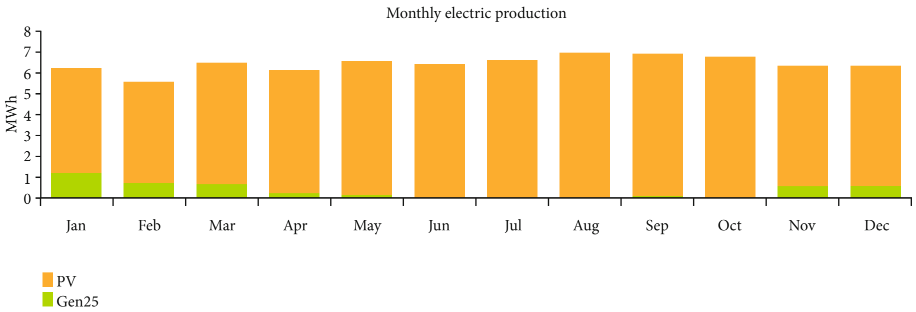

FIGURE 14: Annual monthly electric production of hybrid PV and DG backup.

and demand. The standards of LEPP were calculated for the total time in hours for a year equivalent to 8,760 hours. In case any value of LEPP has been greater than the prescribed one, the decision values were then recalculated. If there was no any deviation from the predetermined value, the optimization procedure was implemented. Then, the optimal size of the hybrid system is obtained corresponding to the lowermost total NPC (also LCOE) which is computed at LEPP equal to zero when the power supply and demand are equally balanced [82].

10. Results and Discussions

The key objective of this research work such as power capacity and cost optimization of the off-grid HRESS for generating electricity matching the needed load demand of the specified location under study has been mentioned at the beginning of the study. In relation to the given data, the optimization of the proposed off-grid HRESS has been implemented using HOMER Pro software and the GWO method developed in MATLAB.

10.1. Results by HOMER Software. This part provides the results obtained from HOMER Pro software. These results include optimization results, results related to sensitivity, and financial and environmental analysis.

10.1.1. Optimal Results. In this work, the optimal configuration of the off-grid HRESS system components in this case study is a 40 kW PV, 25 kW BIOG, 144 generic 1 kWh Li-ion batteries, four in series with 36 strings of system, bus voltage 24 V, and 40 kW converter with a dispatch strategy of cycle charging. This RE system comprises annual scaled solar radiation, scaled annual biomass average, and biomass/biogas price of 6.11 kWh/m^2/day, 0.2 tonnes/day, and \$3.00/tonne, respectively. Figure 3 is the schematic arrangement of the off-grid HRESS for the proposed site. Total NPC, investment cost, and LCOE for the HRESS are \$106,383.50, \$78,500, and \$0.1109/kWh, respectively. Electrical production for PV and BIOG is 72,500 kWh/year and 7,706 kWh/year, respectively. Therefore, the total electrical production of the off-grid HRESS is 80,206 kWh/year. In this case, HRESS is the proposed optimally designed RE-based system combining PV and BIOG and batteries. Figure 13 indicates the annual monthly electric production of the hybrid PV-BIOG-battery storage system in which power output generated by PV is higher than that of BIOG. Capacity factors for PV and BIOG are 20.7% and 3.52%, respectively. Similarly, electricity production for PV/DG/battery and DG only is 77,210 kWh and 779,640 kWh/year, respectively. Annual monthly electric production of PV/DG/battery and DG only is also indicated in Figures 14 and 15, respectively. Figure 16 portrays the cash flow summary for the selected components of the hybrid PV/BIOG/battery system. The investment prices for capital for batteries, BIOG, and PV are \$36,000, \$6,500, and \$28,000, respectively. The capital price for batteries is the highest equivalent to 45.9% followed by the cost of PV with 36.7%. The initial cost for BIOG is 8.3% and thus is the lowest. Also, O&M prices for batteries, BIOG, and PV are \$3,429.92, \$10,825.67, and \$952.75, respectively. BIOG has the highest O&M of about \$71.2 followed by the same category cost of 22.6%. PV has the lowest O&M cost of around 6.3%. Similarly, Figure 17 displays the cash flow summary for the selected components of hybrid PV/DG/battery. The initial

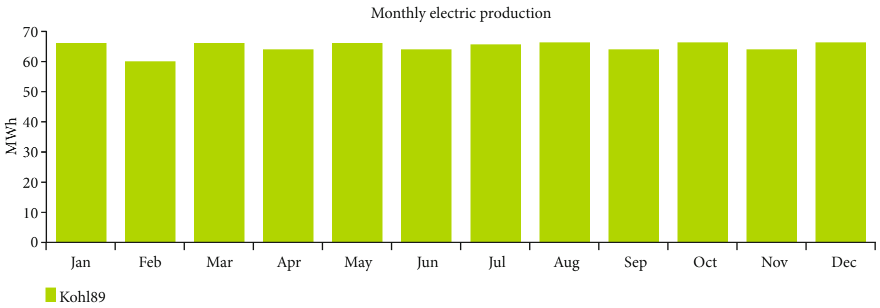

FIGURE 15: Annual monthly electric production DG only.

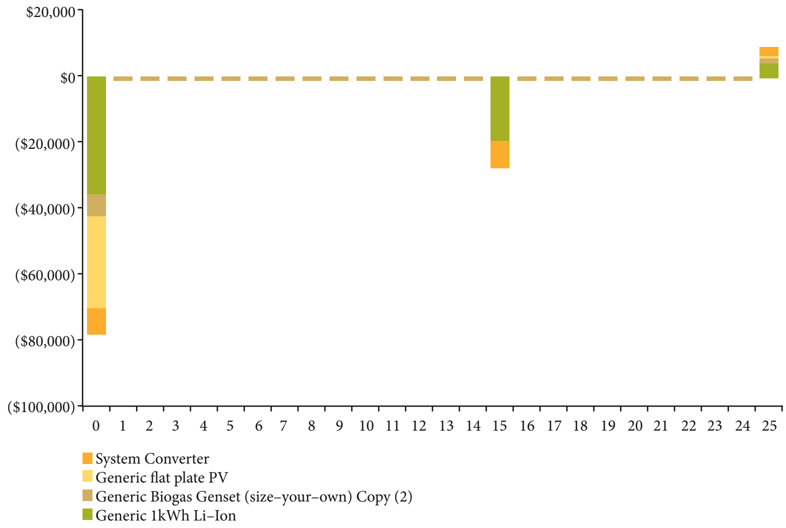

FIGURE 16: Cash flow summary for the selected components of the hybrid PV/BIOG/battery system.

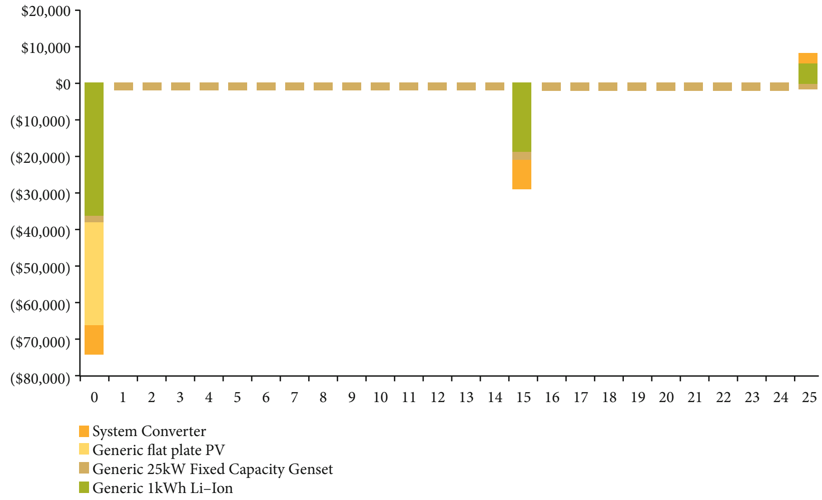

FIGURE 17: Cash flow summary for the selected components of hybrid PV/DG/battery.

costs for batteries, DG, and PV are $36,000, $2,053.06, and $28,000, respectively. The total NPC for the whole system is $122,031.06. NPC for batteries is the highest equivalent to 39.2% followed by the cost of DG backup with 27.6%. NPC for BIOG is 23.7%. As stated in the cost type in Figure 16, the initial cost is the highest accounting for 60.68% of the total NPC. In the same line, if DG only is used continuously (Kohler 89 kW) to supply the load, the total

Table 12: Summarized results of evaluation of electrical power and load.

Parameter	Scenario 1	Scenario 2	Scenario 3
Solar PV production	72500 kWh/yr.	72460 kWh/yr.	NA
BIOG production	7707 kWh/yr.	NA	NA
Battery annual throughput	29961 kWh	29150 kWh/yr.	NA
DG in hybrid production	NA	4750 kWh/yr.	NA
Single DG production	NA	NA	779640 kWh/yr.
Renewable fraction (%)	100	92.1	0
Fuel consumption	23.1 tonnes/yr.	1610 L/yr.	242302 L/yr.
Unmet electrical load	0	0	0
Excess electrical power	6930 kWh/yr.	10725 kWh/yr.	134524 kWh/yr.
Capacity unavailability	0	0	0

NA = not applicable.

Table 13: Summarized results of financial evaluation.

Technology	Investment cost ($)	Replacement cost ($)	O&M cost ($)	Fuel cost ($)	Salvage ($)	Total NPC ($)
System 1						
Solar PV	28000	0	952.75	0	0	28952.75
BIOG	6500	0	10825.67	1081.64	967.31	17440
Batteries	36000	10905. 84	3429.92	0	1848.80	48484
Converter	8000	4541.86	0	0	1038.03	11503.83
System	78500	15447.7	15208.35	1081.64	3854.14	106383.55
System 2						
Solar PV	28000	0	952.75	0	0	28952.75
DG set	2053.06	2053.06	6396.46	25569.55	293.03	33725.74
Batteries	36000	10700.36	3429.92	0	2281.55	47848.72
Converter	8000	4541.86	0	0	1038.03	11503.83
System	74053.06	15242.22	10778.83	25569.55	3612.61	122031.06
System 3						
DG set only	6310	56273.09	425652.67	3847566.29	982.49	4334819.56
System	6310	56273.09	425652.67	3847566.29	982.49	4334819.56

NPC is $4.3 million, COE is $4.52/kWh, and operating cost is $272,726.40. The initial cost for the device is actually lower than the running cost of the machine and therefore is expensive due to fuel cost. Capital for the machine and running cost for fuels is $6,310 (0.14%) and $3.8 million (88.76%) of the total NPC, respectively.

10.1.2. Optimal Off-Grid HRESS versus Other Technologies. Optimization results are presented by comparing the proposed optimized system with other technologies; three scenarios have been formulated: scenario 1 represents the PV-BIOG-battery storage hybrid system, scenario 2 defines the PV-DG-battery storage hybrid system, and scenario 3 describes the DG system.

(1) Evaluation of Electrical Power Generation and Load. Evaluation of electrical power analysis offers details on power generation as explained by the assumed scenarios. Monthly electric generation of PV/BIOG/batteries, PV/DG/batteries, and DG only is shown in Figures 13–15, respectively, and results for electric power based on the three scenarios are summarized in Table 12.

(2) Financial Analysis. Financial analysis has been performed using financial variables of LCOE and NPC. Table 13 indicates the summarized results of the financial appraisal.

10.1.3. Economical Comparison through Break-Even Grid Extension Distance. The range from the main grid at which the total NPC of expanding the grid equals the total NPC of the off-grid system is known as the break-even grid extension distance. This means that if the grid is too far away, the off-grid system is a preferable option. If the main grid is closer to the break-even point, the grid extension is regarded as a superior alternative. A negative distance value means that LCOE of the off-grid micropower system is always cheaper than that of grid expansion whereas the positive distance implies that LCOE of the off-grid system is cheaper than that of grid extension beyond such a distance. Below this break-even distance grid extension (EDL) is cheaper than off-grid HRESS and is not economically viable beyond the distance. Generally, the break-even grid extension can be estimated as follows in Equation (38) [83]:

$$\mathrm{GRID}_{\mathrm{Extension}} = \frac{\mathrm{APP} \times \mathrm{CRF}_{(i,J\mathrm{proj})} - P_{\mathrm{Grid\ extension}} \times \mathrm{Energy\ Demand}}{P_{\mathrm{Grid\ investment}} \times \mathrm{CRF}_{(i,J\mathrm{proj})} + \mathrm{AOMP}_{\mathrm{Grid\ extension}}}, \tag{38}$$

where $\mathrm{GRID}_{\mathrm{Extension}}$ is the estimated break-even grid extension distance (km), $\mathrm{AOMP}_{\mathrm{Grid\ extension}}$ is the operation and maintenance price of grid extension (\$/yr/km), $P_{\mathrm{Grid\ investment}}$ is the investment cost of grid expansion (\$/km), and $P_{\mathrm{Grid\ extension}}$ is the charge of the energy consumption of the grid (\$/kWh). In this specific study, the break-even grid extension distance is presented as follows: Figure 18 presents the total NPC of the proposed 100% renewable system (PV/BIOG/battery or scenario 1) as an alternative option to off-grid HRESS comprising a diesel generator (PV/DG/battery or scenario 2) and diesel-powered generator (DG only or scenario 3). The systems are presented according to their respective break-even grid extension lengths. In scenario 1, the break-even grid extension distance is 0.19 km whereas NPC and LCOE are \$106,383.50 and \$0.1109/kWh, respectively. In scenario 1 of Figure 17, the break-even grid extension range has been estimated to be 0.19 km with a corresponding total NPC of \$106,383.50. As a result, this suggests that if the nearest selected site to which the main grid, say from TANESCO, can be extended is less than 0.19 km away, grid extension is a preferable alternative. Otherwise, the projected off-grid 100% renewable energy microgrid is an excellent investment. Also, in scenario 2 of Figure 17, the break-even grid extension range has been estimated to be 0.48 km with corresponding total NPC and LCOE of \$122,031.10 and \$0.12730/kWh, respectively. Similarly, it implies that if the nearest selected site to which the main grid, say from TANESCO, can be extended is less than 0.48 km away, grid extension is a preferable alternative. If not, off-grid PV/DG/battery is an attractive investment. In scenario 3 as presented in Figure 17, the break-even grid extension range has been estimated to be 77.5 km with corresponding total NPC and LCOE of \$4,337,089 and \$4.52/kWh, respectively. In the same way, it implies that if the nearest selected site to which the main grid, say from TANESCO, can be extended is less than 77.5 kilometres away, grid extension is a preferable alternative. If not, off-grid DG is an attractive investment. Based on the line of sight, the nearest site to which the main grid from TANESCO located in Mbeya city centre may be extended to a specified site is 79.7 kilometres away. It can be observed that in all three scenarios, individual break-even grid distances are less than 79.7 kilometres. Therefore, grid extension is not favoured. That is why most of the isolated rural areas of developing countries employ fossil fuel systems (DG) as an alternative option to grid extension bearing in mind that technological development of renewable energy-based systems is immature. However, the recommended off-grid 100% hybrid renewable energy-based microgrid (PV/BIOG/battery system) is the best option. Description regarding the break-even grid extension lengths of all the three above-named scenarios in terms of total NPCs may apply for further presentation with respect to the corresponding LCOEs as indicated in Figure 19. Figures 18 and 19 show the comparison of break-even grid extension distance versus scenario 1, scenario 2, and scenario for total NPC and LCOE, respectively.

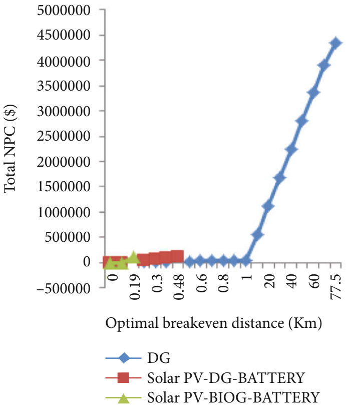

Figure 18: NPC for hybrid PV-BIOG-battery, PV-DG-battery, and DG versus break-even distance.

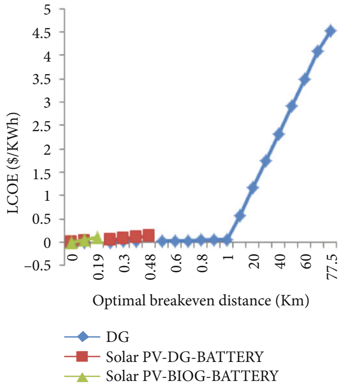

Figure 19: LCOE for hybrid PV-BIOG-battery, PV-DG-battery, and DG versus break-even distance.

Linear equations (39), (40), and (41) have been formulated for drawing the graph for comparing NPC and break-even grid extension of the PV/BIOG/battery, PV/DG/battery, and DG only, respectively, as follows:

$$y_1 = 559913.2\, x_1 - 0.008, \tag{39}$$

$$y_2 = 254231.5\, x_2 - 0.02, \tag{40}$$

$$y_3 = 55962.4\, x_3 + 3. \tag{41}$$

Note 1. All y and x indicate total NPC and break-even grid extension distance, respectively.

Similarly, linear equations (42), (43), and (44) have been formulated for drawing the graph for comparing LCOE and break-even grid extension of the PV/BIOG/battery, PV/DG/battery, and DG only, respectively, as follows:

$$y_4 = 0.5837 x_4 - 0.000003, \tag{42}$$

Table 14: The comparison of the GHG emissions produced by the proposed 100% RE micropower system (HRESS) versus other technologies under specified scenarios.

Pollutant	Scenario 1 (PV/BIOG/BB)	Scenario 2 (DG/BIOG/BB)	Scenario 3 (DG only)	Unit
Carbon dioxide	0.531	67,641	635,966	kg/year
Carbon monoxide	0.00589	422	2908	kg/year
UNHC	0	18.6	174	kg/year
Particulate matters	0	2.53	15.4	kg/year
Sulphur dioxide	0	166	1553	kg/year
Nitrogen oxide	0.00368	397	308	kg/year

UNHC = unburned hydrocarbons.

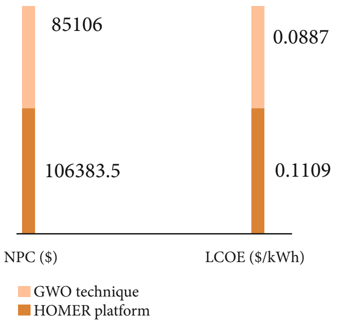

Figure 20: Graph of NPC and LCOE for off-grid HRESS using HOMER and GWO platforms (LEPP = 0).

$$y_5 = 0.2652\,x_5 + 0.000004, \tag{43}$$

$$y_6 = 0.0583\,x_6 + 0.00175. \tag{44}$$

Note 2. All y and x indicate total LCOE and break-even grid extension distance, respectively.

10.1.4. Results of Sensitivity Analysis. Input variables include variations in electricity supply requirement, energy resources, and fuel costs. Several sensitive input parameters are taken into account for the selection of optimal configuration of off-grid HRESS to meet the energy demand. Sensitivity analysis indicates that an increase in annual scaled solar radiation from 6.11 to 7.5 kWh/m^2/day at fixed biomass feedstock and electrical load reduces the total NPC, LCOE, and operating cost of the optimized system. The total NPC, LCOE, and operating cost of the proposed optimal off-grid hybrid PV/BIOG/battery are $106,383.50, $0.1109/kWh, and $1,755.95, respectively, which are reduced to $101,584, $0.106/kWh, and $1,454, respectively. Similarly, the total NPC, LCOE, and operating cost when the backup system is DG instead of BIOG, that is, hybrid PV/DG/battery, are $122,031.10, $0.1273/kWh, and $3,021.43, respectively, which are reduced to $109,700, $0.114/kWh, and $2,245, respectively.

10.1.5. Results of Environmental Analysis. The impact of greenhouse gas (GHG) emissions produced from the proposed optimal off-grid HRESS consisting of PV, BIOG, and batteries is also compared with GHG emissions from assumed technologies. Table 8 indicates the comparison of GHG emissions produced by the proposed 100% RE micropower system (HRESS) versus other technologies under specified scenarios. Table 14 indicates a comparison of the GHG emissions produced by the proposed 100% RE micropower system (HRESS) versus other technologies under specified scenarios.

10.2. Results Obtained by GWO Method. This specific part of the research article presents the optimization and sensitivity results of the off-grid HRESS achieved via the application of the GWO platform as follows.

10.2.1. Optimization Results of Balanced Generated Power Supply-Demand System (LEPP = 0). As it has been mentioned before, the average daily electricity consumption is 511.1 kWh/day (baseline), peak power capacity is 30.31 kW, and load factor is 0.71. For the hybrid electric system to supply sufficient power to satisfy the load, generated electricity should be equal or greater than the highest power capacity. The off-grid HRESS has been optimized when LEPP equals zero denoting no shortage of power. In other words, generated power supply and energy demand are well balanced. The analysis of the optimized system by the GWO method shows that overall NPC and LCOE are $85, 106 A, and $0.0887/kWh, respectively. The use of AI optimization technique (GWO) has further reduced the financial metrics of power generation up to around 20% when compared with soft computing tools (HOMER). Figure 20 indicates the graph of NPC and LCOE for off-grid HRESS using HOMER and GWO platforms (LEPP = 0).

10.2.2. Sensitivity Analysis Results of Unbalanced Generated Power Supply-Demand System. The sensitivity analysis is carried out to find out the effect of system reliability in reflection on financial performance. Here, the assumption is made that generated power and energy demand are unbalanced [84]. The application of the GWO algorithm is employed by considering the unbalanced condition of the designed system. In this research article, LEPP is considered to be the sensitivity's variable; thus, the analysis of the optimized system has been evaluated based on the variation of estimated magnitudes of LEPP, that is, 0.04 and 0.06.

It has been witnessed that when LEPP equals 0.04, the configuration of off-grid HRESS reveals the overall NPC of $79,545.992 and LCOE of $0.0316/kWh. The variation of overall NPC of the designed off-grid HRESS is now less than that in a balanced energy system when LEPP equals zero.

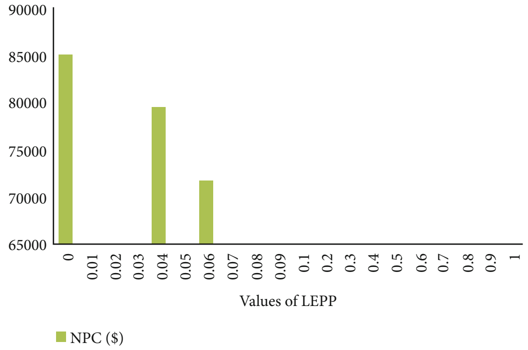

Figure 21: Graph of NPC for optimization and sensitivity results of the system by GWO method.

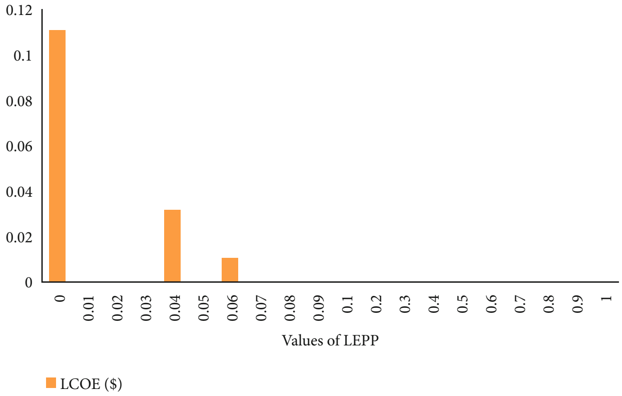

Figure 22: Graph of LCOE for optimization and sensitivity results of the system by GWO method.

The diminution in extra power can be ascribed owing to the reduction in the capacity of the solar PV array. Similarly, when LEPP equals 0.06, the off-grid HRESS configuration has an overall NPC of $71,747.36, and its corresponding LCOE equals $0.0.0102/kWh. It implies that at a given condition of LEPP which equals 0.06, the overall NPC of optimal HRESS is further decreased up to at least 20% in comparison with the balanced condition of generated capacity and energy demand. The extra power generation is minimized owing to the decline in the capacity of the solar PV module. In this case, maximum power of the designed system is not taken into account and attributed to the reduced extra power. Figures 21 and 22 indicate the graphs of NPC and LCOE for optimization and sensitivity results by the GWO method.

11. Comparison of Findings Acquired from Other Related Configurations

For the purpose of understanding clearly the importance owing to the application of the GWO algorithm, the performance of the proposed off-grid HRESS (presented in this paper) is related to the other optimal hybrid renewable energy-based systems consisting of similar configurations consisting of renewable energy sources, that is, solar PV and biogas fuel. Dissimilarities are mainly in terms of storages, electrical loads, and metaheuristic optimization approaches. The comparison of results from other related configurations is discussed as follows.

First, the proposed HRESS is compared with the system consisting of solar PV, biogas fueled generator, and storage system comprising batteries and hydro pumped storage system [85]. The system employs one upper reservoir without the lower one [85]. The system is designed to power a radio transmitter with power capacity, consumption, and load factor of 25.54 kW, 356.38 kWh/day, and 0.58 [85]. The study presents the optimization of the hybrid system using two metaheuristic techniques such as WCA (Water Cycle Algorithm) and MFO (Moth Flame Optimization) which are compared with the genetic algorithm (GA) [85]. These techniques have indicated the highest convergence rate in the optimization results. WCA shows an area of solar PV panels equal to 548.67 square metres producing power equivalent to 69.2 kW, biogas fueled generator capacity is 16 kW, number of batteries equals 21, capacity of the converter is 30 kW, capacity of the top reservoir is 2,081.5 cubic metres, total NPC is $813,319, and LCOE is $0.4864/kWh [77]. Similarly, MFO indicates an area of solar PV modules equal to 549.2 square metres producing power equivalent to 69.3 kW, capacity of biogas-driven generator is the same as in WCA, the number of batteries is the same as in WCA, capacity of the converter is the same as in WCA, capacity of the upper reservoir is 2,083 cubic metres, total NPC is $813,865, and LCOE is $0.4865/kWh [85].

In the second configuration, the HRESS is also compared with the configuration containing solar PV, biowaste, and fuel cell (hydrogen storage tank). The configuration is intended to generate power to serve the annual load profile equal to 269.15 MWh [86]. The paper presents the system optimized using the WOA (Whale Optimization Algorithm) method which is the PSO (particle swarm optimization) technique by bearing in mind the existence of components for a lifetime of 20 years. The optimal system configuration is the cheapest in comparison with other combinations. The system has a total NPC of $2.820 million and LEPP equal to 0.0029 [86]. Similarly, LCOE of the same optimal system equals $0.5238/kWh [86]. The suggested optimization method for the optimal design of a hybrid system is superior to PSO. The WOA method presents lower total NPC, accuracy, higher convergence velocity, and reliability [86].

The third configuration consists of solar PV, battery, and pumped storage systems having upper boundaries without a biogas generator bearing in mind that the proposed HRESS has a biogas generator in addition to solar PV but without pumped water storage [87]. The designed system is aimed at supplying power for an isolated island in Hong Kong using renewable energy sources for 100% [87]. The daily power consumption and peak power are, respectively, 250 kWh and 50 kW [87]. The system provides the viability study and financial analysis of the given energy storage systems. The storage energy systems are investigated in terms of LCC (life cycle cost) and practical feasibility. The analysis using LCC is useful for determining which is more cost-effective between the energy storage by the battery bank and pumped water [87]. The study has compared three options such as novel deep cycle battery, traditional battery, and combined pumped hydro and battery energy storages. The LCC and LCOE for the optimal storage system combining pumped hydro and battery energy storage schemes are $2,394.901 and $1,916/kWh, respectively [87].

The fourth configuration is also constituted by solar PV, biogas power system, and battery storage system. The system has been analyzed using a deterministic method to satisfy a proportional scaled-down demand of Kenya, one of the countries located in East Africa [88]. In the paper, it has been assumed that solar panels covering an area equivalent to 20,000 square metres produce a capacity of 5 MW. Also, a biogas generator can produce power only if the power output declines below 40% of the rated size (2.4 MW) while its efficiency is 70% [88]. The optimal sizing ratio of power generation sources of biogas generator to solar PV is 2.4 : 5. By using the PSO algorithm, the study has shown lower LCOE in the hybrid system than that of the biogas generator. On the other hand, LCOE becomes lower at a discount rate below 8% and stipulated prices of the system components [88]. In 2012, for instance, at a discount rate of 8% with lower and upper boundaries of given costs, the optimal results of LCOEs were found to be $0.39/kWh and $0.42/kWh, respectively [88].

Generally, different metaheuristic optimization results indicate an effective design of a hybrid energy system with less technical and financial costs as likened to available designs in the literature.

12. Conclusions, Recommendations, and Research in the Future

In this paper, HOMER and GWO method have been utilized for acquiring the technoeconomic analysis of the optimal design of a PV-BIOG-battery hybrid system for delivering electricity to Simboya village in Mbeya Rural District, Mbeya region, Tanzania. Firstly, based on the application of the HOMER platform, conclusions of this research work are presented as follows: Technical and economic viability analysis for a 100% hybrid renewable electric system has been carried out intending to generate electricity for Simboya village, Mbeya Rural District, Tanzania. This study includes an optimized design, and a comparative study of PV-BIOG-battery, PV-DG-battery, and DG only is carried out. Additionally, the break-even grid extension distance of the individual aforementioned technology has been evaluated based on the assumption that the microgrid power system may take power from the central grid. Furthermore, the study has performed sensitivity and environmental analyses. The country is located in tropical areas, and therefore, electrical load profiles for the area of study have been considered the same due to the lack of extreme climate change variation in a year [58]. A residential load equivalent to 50% of accrued power requirement is the highest. The load for street lighting is the lowest. This study has indicated that the lowest-price hybrid configuration of PV-BIOG-battery is capable of meeting the energy demand at LCOE of $0.1109/kWh with almost negligible GHG emissions. This LCOE is equivalent to or less than the grid power price from TANESCO in the range of Tanzanian shillings (TZS) 242.2-306/kWh (0.104–0.14 USD/kWh; 1 USD equals 2,319.55 on 18.09.2020) [89–91]. Furthermore, the cost of the proposed system is also even less than the projected LCOE by 2035 for renewable-based microgrid in SSA that is expected to drop to $0.2/kWh in electricity generation projects with around 90% renewable energy fraction [92]. The price of renewable energy-based electricity might not all the time be cheap for isolated areas, and thus, LCOE can further be reduced by support through subsidies based on specific renewable technologies [9, 93]. This 100% RE system has the least break-even grid extension distance of about 0.19 km implying the least NPC. Among the three technologies, DG only has the highest LCOE and LCC due to the highest running cost caused by high fuel costs. LCOE for DG only is at least four times that of the PV-BIOG-battery hybrid system. The study has also indicated that DG only produces the highest GHG emissions. Sensitivity analysis shows that an escalation of yearly scaled solar energy from 6.11 to 7.5 kWh/m^2/day at fixed biomass feedstock and electrical load demand decreases the total NPC, LCOE, and operating cost of the optimal hybrid configuration. Moreover, minimum daily mass equal to 0.315 tonnes is greater than the estimated daily minimum requirement of biomass which is equal to at least 0.2 tonnes. This lowest value can drive a biogas generator to produce power of 25 kW. The estimated residential load for Simboya village is equal to 30 kW and is the highest at almost 50% while power consumption for the street lighting electrical load is the least being equivalent to 0.5% of the overall energy demand.

Secondly, in conformity with the application of the GWO technique, the conclusions of this study are provided as follows: Results of the technoeconomic analysis of the optimal HRESS when generated power and energy demand are matched (LEPP = 0) have been presented. The sensitivity analysis of the technoeconomic analysis of the system for the assumed values of LEPPs (LEPP = 0.04 and LEPP = 0.06) more than zero has indicated that the increased LEPP provides the optimal HRESS with the minimized size of components. In general, the application of a metaheuristic approach (GWO) has exhibited better technoeconomic performance of the off-grid HRESS in comparison with the soft computing tool (HOMER platform). In other words, the use of the GWO technique shows the decline of the financial metrics of the system. The optimal HRESS is a promising solution for providing electricity to rustic and isolated locations including the site under study and other places worldwide with similar situations.

For future study, the optimal HRESS can be expanded by integrating the system with other energy sources and storage energy systems and further analyzed using an advanced approach such as metaheuristic methods in order to build up the enhanced body of knowledge regarding the solutions to optimization problems.

Data Availability

Data can be obtained from the corresponding author.

Ethical Approval

There was no ethical violation or misconduct in this research work. The research was conducted after getting a permit from the regional commissioner's office in Mbeya region, Tanzania.

Disclosure

This research work is entirely the product of the authors' initiatives.

Conflicts of Interest

The authors have no conflict of interest and therefore are responsible for the contents and preparing this article.

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