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PV Based Microgrid for Remote Area Electrification in Nigeria: A Systematic Review of Concepts and Extant Strategies

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Systematic Review Article

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ABSTRACT

Centralized power generation, transmission and distribution system operations in Nigeria can no longer deliver affordable and reliable electricity to remote households, both on and off the national grid. Therefore, a balanced approach, through renewable energy generation is the best option that would potentially lead accelerated journey to full electrification in the country. Renewable energy has become a panacea to energy problems worldwide because it is clean, environmentally friendly and ultimately cheaper. Due to the massive capacity of Nigeria to generate electricity from its numerous green energy resources, it has become crystal clear that access to sustainable and reliable energy in Nigeria is required for proper economic and social development. This work is based on an extensive review of recent experiences of more than 120 papers covering mostly the

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off-grid PV sector in the past 15years. The review included: scientific journals, conference papers, (PhD) theses, books and scientific reports from governments/NGOs and publications from energy institutions. A comprehensive review of relevant concepts and current microgrids optimization strategies applied to sizing, siting, load estimation and energy management has been conducted. Future research directions and potential of PV based microgrids for rural electrification have equally been specified.

Keywords: Renewable energy system; PV microgrids; rural electrification; microgrid optimization.

1. INTRODUCTION

In recent years, issues of climate change and the rise in energy demand have become major concerns globally. Greenhouse gases such as carbon dioxide, methane, fluorinated gases, nitrous oxide, carbon monoxide, are rising by the day. Also, the social and economic development of any country has a direct link with energy demand and per capita consumption [1]. According to research carried out by the United Nations Environment Program (UNEP), up to two billion people around the world have no access to grid connected electricity most of which are underdeveloped communities [2]. In dealing with these issues and challenges, renewable energy resources are the best alternative [3]. Renewable energy resources are environment-friendly, unlimited, inexhaustible and sustainable [4]. These sources have a high potential to replace conventional sources of energy and currently the whole world is looking forward to effectively utilizing these resources in the best possible way to generate electricity [5].

“Rural electrification refers to the means and processes of electrifying rural and remote areas” [6]. In Nigeria, electricity utility is far from within the reach of majority of rural dwellers whose population is about six-five per cent (65%) of the total populace [7,8]. With demand for electrical energy far from matching its supply, the rural dwellers face major challenges of inadequate and epileptic power supply made worse by poor quality of services. Rural areas are the worst hit in terms of poor access to electricity supply, particularly the off-grid communities, which have always been without electricity supply and have resigned their fate to; the use of oil lamps, kerosene lanterns and other types of unhealthy and dangerous sources of light for daily living. This development is inimical to the socio-economic development of the country as it has created an atmosphere that is not conducive for Micro, Small and Medium Enterprises (MSMEs), being the key drivers of the country’s economic growth [9]. Appropriate technology through which electricity can be optimally supplied to remote communities has been identified as one of the major solutions to address the problems of rural electrification [10].

Again, in rural electrification, extension of the main grid to remote communities is a serious challenge. In addition to posing technical challenges, it is costly and inefficient hence the need for Nigeria to find alternative means for rural electrification. Consequently, focus has been shifted to micro-grids especially those that utilizes renewable energy resources. Micro-grids are viewed as a possible solution due to their ability to function independently from the main grid and because they can also be designed to interconnect with the main grid should there be an opportunity for extension of the grid to the remote community in the future. Micro-grids design offer a far better option for providing electricity than putting large sums of money in transmission and distribution facilities. The integration of renewable energy generations in microgrid is the only practical solution to meet rural electrification needs [11]. The more remote the location, the more competitive microgrids get since it is much cheaper to produce electricity locally than to extend utility grids into the mountains or through the forests [12]. However research on the design and development of community micro-grids, economic aspects of micro-grid planning and operation as well as value propositions of this technology is still modest. In addition, renewable energy based micro-grids especially those designed for rural electrification purposes in Nigeria face a lot of issues as regards their implementation. These fall into the categories of general, technical, economic and financial, legal and regulatory, institutional, social and society and sustainability issues. Various researchers have highlighted these issues [13-18].

Due to various government interventions and regulatory policies regarding subsidies, feed-in-tariffs, market friendly policies among others, renewable energy systems are increasingly becoming more cost-effective and a major share of the power plant mix globally [19]. "As such, research has shown that renewable energy accounts for almost one-third of the total electrical power generation globally" [20,21]. Out of the emerging renewable energy systems commercially available for electricity generation, wind and solar PV have been given extensive research attention and practical implementation. This is because the efficiencies of these technologies are consistently being improved and can be well adopted both for large scale applications and in small form in areas with sufficient resource. For instance, it is reported that a solar generating facility occupying approximately 0.3% of the land mass in North Africa has the potential to meet all the energy demand of the European Union countries [22]. Due to its modularity, solar PV technology remains the most commonly used renewable energy system and has been able to meet to a large extent, the energy demands among off-grid household consumers. The output of a solar PV panel is dependent on the availability of the solar resource. What this means, is that the power output of a solar PV panel depends on the degree of intermittency of solar resource and daily weather fluctuations. In order to compensate for the setback caused by intermittency of resources, the use of hybrid systems is usually proposed. Another means of clipping the effects of intermittency is the use of energy storage systems [23]. This will reduce the effect of resource availability fluctuations and help in getting a fairly constant output [24,25]. Extracting the maximum obtainable output from the solar panel can also contribute to a technically and economically efficient energy system. This requires that all components are optimally sized.

There are quite a number of research works on the design of a renewable energy based microgrids for rural electrification with focus on solar technology. In PV micro-grid design for rural electrification, [26] used centre of moments for central PV system sizing/location, simulated annealing for network structure optimization and load flow based parametric analysis for confirming the PV micro-grid structure. The results showed that the centre of moments approach can be used for identifying the optimal location of the central PV source. Namaganda-kiyimba [6] deployed Mixed Integer Linear Programming (MILP) to optimally size the PV micro-grid while Density Based Spatial Clustering of Applications with Noise (DBSCAN) algorithm helped to aggregate load and meteorological data. In the study, there was absence of field work and user-end load management. A combination of design thinking and model-based design methodology was deployed in [27] to select a suitable micro-grid configuration and to develop a smart micro-grid model, though not much was done to further validate the model, for instance, using data from other communities. In modelling integrated biomass and photovoltaic generators for rural electrification, [28] used a bottom-up modelling approach to generate a stochastic rural household(s) load profile. In examining the state of the art of artificial intelligent (AI) techniques and tools in power management, maintenance and control of renewable energy systems (RES), [29] carried out literature review from highly regarded journals and review of reports relating to the study in the last ten years to draw meaningful and significant results which showed that Artificial Neural Network (ANN), Back Propagation Neural Network (BPNN), Adaptive Neuro-Fuzzy Inference System (ANFIS) and Genetic Algorithm (GA) are reliable AI techniques used in renewable energy systems. Youssef et al. [30] reviewed the role of AI algorithm in different aspects of PV systems, drawing comparison between conventional and AI methods and outlining the contributions of the review works. The research work however, lacked quantitative evaluation.

Although the aforementioned studies have covered a vast range of contemporary issues on the design of a sustainable and renewable energy based microgrids for rural homes in Nigeria, and given the prospects of renewable energy systems in providing clean and affordable energy at all income-levels, more research work is required. Again, to close the knowledge gaps and boost understanding of the existing strategies and emerging issues surrounding off-grid renewable energy systems implementation and acquisition for household use in Nigeria, this paper, which is a state-of-the-art survey, will answer the following research questions:

- What is PV Microgrids and what are the barriers and factors responsible for the growing interest in the development of PV Microgrids design for Nigeria's rural communities?
- What are the underlying issues in PV electrification generation and energy storage?

- What Artificial intelligence Optimization techniques and tools are currently deployed in microgrids design for rural electrification?
- What are the current literature regarding load estimation, PV source siting, PV sizing and end user energy management research?
- What are the future research directions and potential of PV based microgrids for rural electrification?

2. APPROACH ADOPTED FOR THE SYSTEMATIC REVIEW PROCESS

The review adopts a comprehensive and structured approach. Detail of how the literatures were selected is shown in Fig. 1.

3. CONCEPT OF MICROGRIDS, ADVANTAGES AND DRAWBACKS

Zhang et al. [31] "describes microgrid as a cluster of loads and relatively small energy sources operating as a single controllable power network to supply the local energy needs". "It can equally be seen as a small grid in which distributed generations and electric loads are placed together and controlled efficiently in an integrated manner" [32]. It contributes to an efficient operation of distributed generations by operation planning considering grid economics and energy efficiency. Microgrids usually consist of distributed energy resources, power conversion equipment, communication system, controllers, customers/loads and energy management system to obtain flexible energy management [33]. The schematic diagram of a solar PV microgrid is also illustrated in Fig. 2.

The advantages of microgrids have been broadly classified into environmental and economic benefits. However, other advantages of microgrids are seen as; significant reduction in energy losses and improvement in the utilization of renewable energy resources. The reliability of the systems is also improved by connecting multiple generating units to ensure continuous demand supply. Also, the decentralization of distributed generators allows the microgrid in cases of outages to operate independently leading to a reduction in the adverse effects of outages. Moreover, one of the advantages of microgrids is to enhance energy management which means, properly matching the supply and demand to reduce the energy supplied from the grid [34,35]. In addition, renewable energy resources are environmentally friendly and will never die out as they are continuously replenished. However, because of their stochastic and intermittent nature, affording continuous electricity from a power system with integrated renewable energy resources is very challenging. One of the most efficient technologies providing anticipated unit cost reductions, which makes the investment in these systems looks extremely attractive, is energy storage systems. Their integration along with renewable energy resources is assumed to provide fundamental advantages to the microgrid by maintaining the balance between generation and consumption, and improving the reliability of the power grid [36]. An example of a microgrid in dual mode is given in Fig. 3.

The microgrid in Fig. 3 has a photovoltaic farm, wind turbine farm, various demand, diesel generators and battery energy storage system. The microgrid can operate in both in stand-alone and grid-connected modes through the point of common coupling. In grid-connected mode, both sources will supply the residential and industrial demand during their availability. The storage system will store surplus energy for back up supply when needed. However, any deficiency in energy will be covered by the grid. In stand-alone mode, the diesel generator acts as backup and supply the demand.

4. MICROGRID FOR RURAL ELECTRIFICATION IN NIGERIA

Access to sustainable and reliable energy is necessary for proper economic and social development. The United Nations General Assembly in its resolution, declared the year 2012 as; "The International Year of Sustainable Energy for All". Therefore, access to affordable and modern energy services is essential to attain sustainable development" [37]. Electricity supply in Nigerian is unreliable. The country has an installed generation capacity of 15,000MW, but the available generation as at the end of April 2013 was a paltry 4000MW which cannot meet the expected demand of over 170 million people [38]. However, electricity generation capacity of Nigeria reached a record 5,000MW in May, 2024 [39]. "Currently, about 40 per cent of Nigerians or more lack access to reliable electricity and the limited generation is through the use of expensive diesel generator. Also, the areas connected to the national grid lack constant supply of electricity not to mention those living in remote regions of the country that have no hope of receiving electricity. In particular, for rural areas, electricity is a key resource for meeting basic human needs and microgrids may be the best way to deliver that electricity" [40]. "Because of dramatic cost declines in solar photovoltaic and energy storage, microgrids has provided electricity to about 150 million people in the past decade [38]. Microgrids with high penetration of renewable energy resources are becoming popular for rural electrification in Nigeria. However, they are faced with challenges and barriers such as; intermittency of renewable generation sources like wind and solar energy, non-uniform distribution of renewable energy resources as well as power control issues [38]. However, some of these drawbacks are offset by their several advantages such as; proximity to loads which minimize power losses, improvement in power quality and reliability, flexibility that enhance fast rural electrification. Integration of microgrids into main grids can reduce transmission and distribution line losses, increase grid resilience, lower generation costs and reduce requirements to invest in new utility generation capacity [38]. All these benefits make microgrids suitable solutions to rural electrification problems in Nigeria. Other factors that contribute to the growing interest in microgrid design for rural electrification can be summarized thus [41,42]:

- Environmental: Government is not being encouraged to invest in the construction of new transmission lines, consciousness of the public as per negative impact of greenhouse emission.
- Economic: Avoidance of transmission and distribution costs, fear of the risky nature of large scale plant investments and deliberate attempt to take advantage of profit margins within the competitive market.
- Technical: Observed increase in power demand by consumers, need for electronic metering and control equipment, excellent performance of small power technologies being currently utilized.
- Political: Attempt to avoid dependence on supply chain in a centralized system, reduce overdependence on fossil fuel and expansion of available power sources.
- Social: Current awareness on the need to avoid greenhouse emission and the interest towards energy sustainability, autonomy and security.

5. PHOTOVOLTAIC (PV) ELECTRIFICATION GENERATION

"Photovoltaic (PVs) are semiconducting materials that convert sunlight into electrical energy. The PV system electrical energy generation is dependent on the photo-electric effect of the PV material and on the amount of incident radiations received by the solar panel" [43]. It consists of two semiconductor layers usually monocrystalline or polycrystalline that are sandwiched and doped such that one layer has too few electrons - p-type and the other has many electrons - n-type [6]. The design characteristics of the PV material determine the electrical output of the PV system. Some of the electrical parameters used by manufacturers to define the characteristics of a PV system are presented in Table 1.

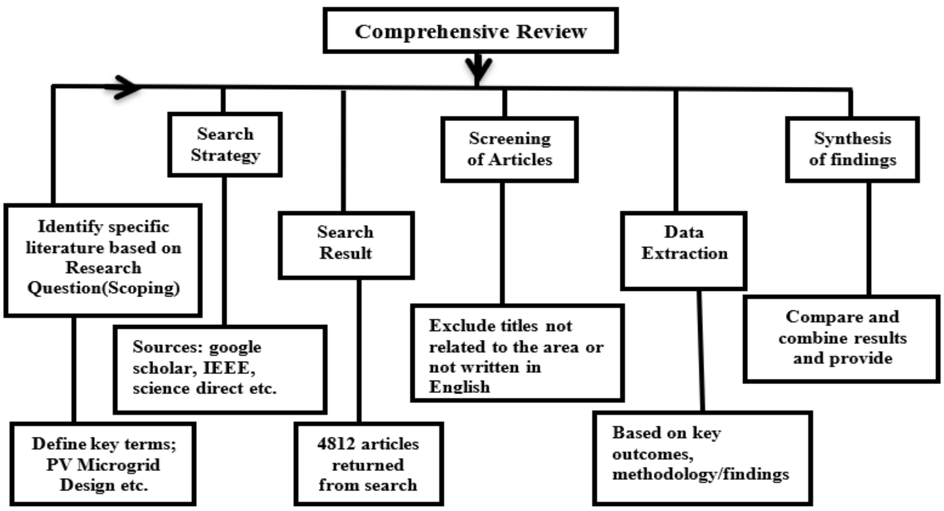

Fig. 1. PV Microgrids Design for Nigeria's Rural Communities (Researcher, 2024)

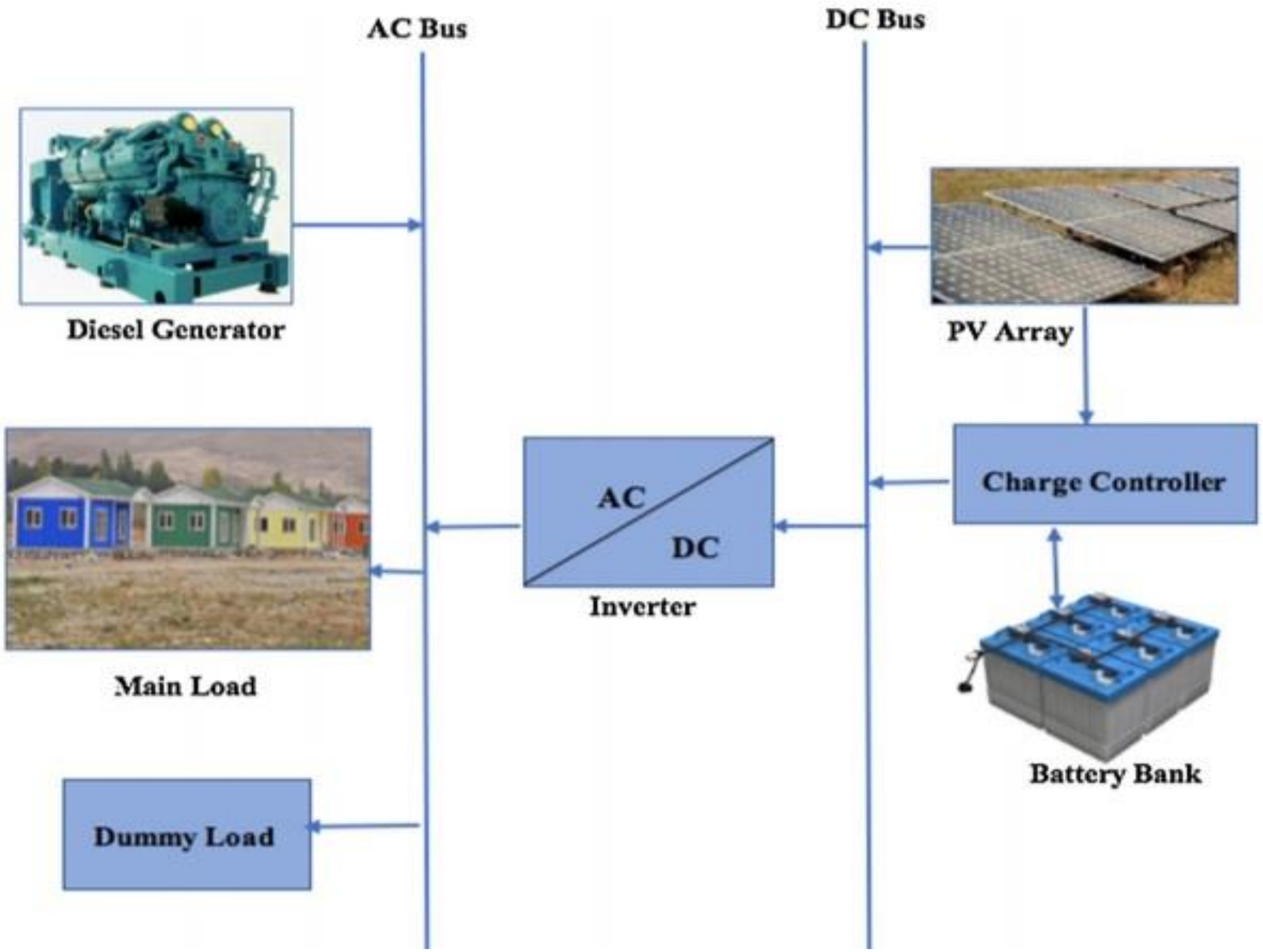

Fig. 2. A schematic diagram of solar PV Microgrid

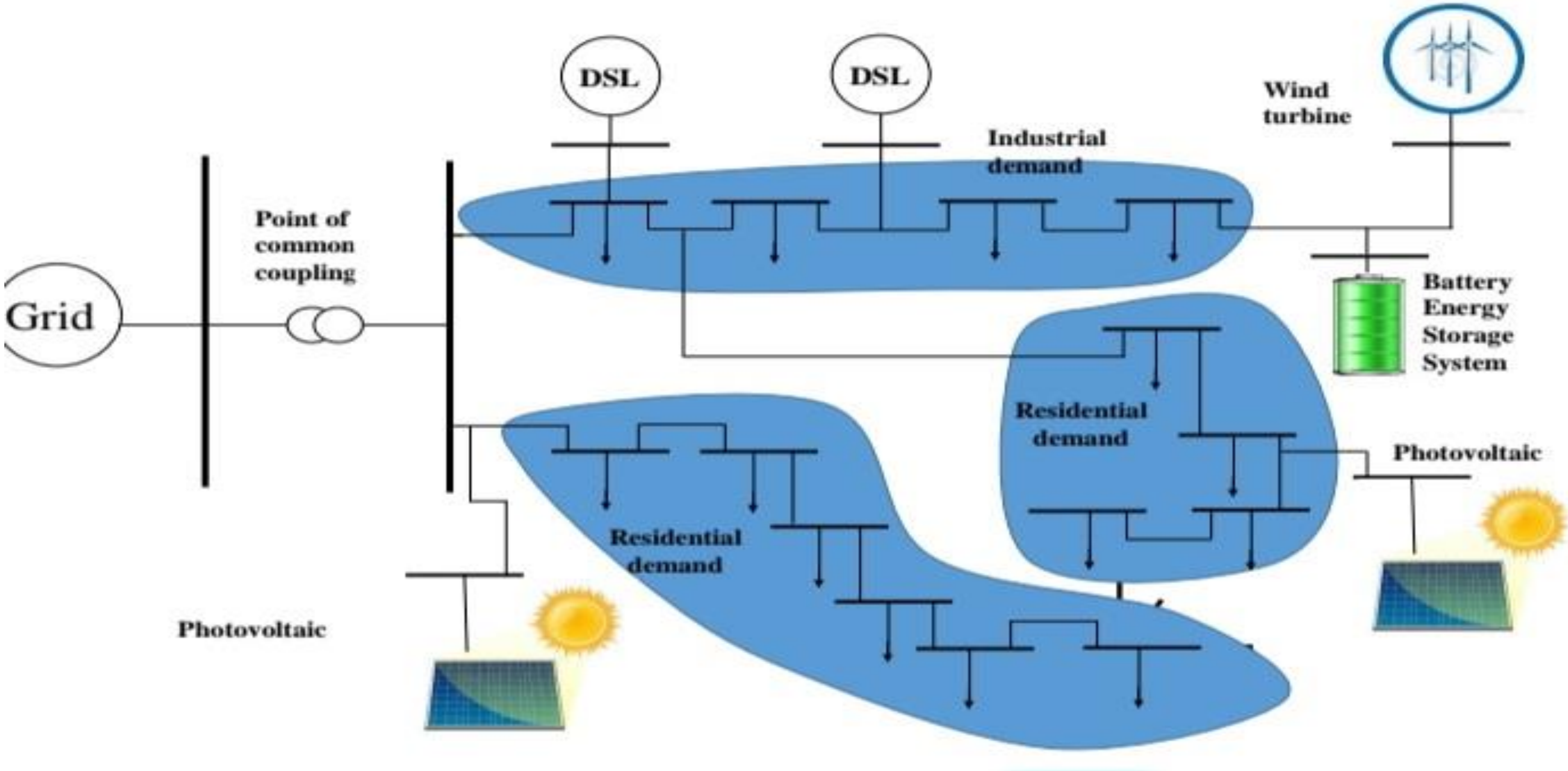

Fig. 3. Grid connected and stand-alone modes microgrid for both a residential and industrial demand

Table 1. PV System Electrical Parameters [6,43,44]

Parameters	Definition
Efficiency, η	This is the ratio of the energy output from the solar cell to the input energy from the sun.
Open-circuit voltage, V_{OC}	This refers to the maximum voltage supplied at no-load or no-current.
Short-circuit current, I_{SC}	It is defined as PV module supply current when the module voltage is zero or short-circuited.
Voltage at maximum power point, V_{MPP}	This is the PV module voltage for maximum power supply or the ideal voltage to generate maximum power.
Current at maximum power point, I_{MPP}	This is the PV module current for maximum power supply or the ideal current to generate maximum power.
Power at maximum power point, P_{MPP}	This refers to the point whereby the PV module can supply maximum power to the load.
Fill factor, FF	It is the ratio of the maximum power point power (P_{MPP}) to the power obtained by multiplying $\mathbf{V_{OC}}$ by the short-circuit current.

A typical PV module with I-V and P-V characteristics curve is shown in Fig. 4. The series losses & shunt losses, and mismatch losses are resulted due to uniform soiling and non-uniform shadings of the solar PV system respectively.

6. ENERGY STORAGE SYSTEMS (ESS)

This is the process of converting electrical energy into a form that can be kept in different types of storage. Their technologies have been found to be the suitable solution for the problems associated with the proliferation of diesel generators. Energy storage systems have different functions when installed in a distribution system, and some of these functions can be summarized as follows [36,45,46,47].

- To facilitate the integration of renewable energy sources into the grid, enhance the quality of the energy supplied and increasing their penetration rate.
- To reduce peak demand problems by providing energy when needed hence eliminating the extra operation of diesel generators during the peak periods.
- To provide a balance between generation and consumption and improves the management and reliability of the grid.
- To provide rural areas with their energy needs, in situations where it is challenging to set up new grid connection plans.
- To reduce the energy imported from the electrical grid in grid-connected systems.
- To improve the overall stability of the electrical system and make the elimination of power disturbances possible.

Numerous energy storage system technologies are available in the market, and the selection of the suitable storage technology depends solely on factors such as; power rating, discharge time, suitable storage duration, lifetime, life cycle cost, capital cost, round trip efficiency [48]. They can be categorized into: electrical, mechanical, thermal, electromechanical, magnetic, chemical and thermochemical [36,47]. Fig. 5 shows several types of energy storage systems and their examples.

6.1 Battery as an Energy Storage System (B-ESS)

PV microgrid systems stores energy by battery bank during the sunshine hours in order to meets the load demand when the energy generated by the solar panels is insufficient. The cost of battery significantly contribution to the overall long term operating costs of the microgrid. It is desirable that the batteries chosen for PV applications have a low capital cost, high efficiency, low maintenance cost and long life [6]. Some of the most common battery technologies for household applications are presented in Table 2, [36,49].

7. ARTIFICIAL INTELLIGENT (AI) OPTIMIZATION TECHNIQUES AND TOOLS USED IN PV MICRO-GRIDS DESIGN

7.1 Artificial Intelligent (AI) Optimization Techniques

Artificial intelligent techniques are developed intelligent computer programs, built by the application of science and engineering procedures in order to represent natural occurrence. AI technique can be thought of as the ability of a machine to perform functions that characterize human thought [51]. Examples of AI optimization techniques include: genetic algorithm (GA), particle swarm optimization (PSO), bacterial foraging algorithm (BFA), artificial bee colony (ABC) algorithm, bio-geography based optimization (BBO), gravitational search algorithm (GSA), Cuckoo search (CS), simulated annealing (SA), harmony search algorithm (HSA), ant colony algorithm (ACA) and a hybrid of different AI techniques. One of the several advantages of AI methods is their ability to investigate non-linear variations of renewable energy system components and perform multi-objective optimization, but AI optimization techniques are usually complex in terms of implementation as compared to classical optimization techniques [51,52]. Key features, merits and demerits of selected artificial intelligence optimization techniques are presented in Table 3.

7.2 Software Tools for Simulation of PV Based Microgrids

When designing and optimizing a PV based microgrid, choosing the right software tools is critical to ensure an efficient and cost effective system. Relevant details of key softwares for PV based microgrids are summarized in table 4.

8. LITERATURE SURVEY OF EXISTING MICROGRIDS OPTIMIZATION STRATEGIES APPLIED TO MICROGRIDS LOAD ESTIMATION, SITING, PV SIZING AND END USER ENERGY MANAGEMENT

Some of the current optimization techniques applied to optimally design a PV Microgrids particularly in the areas of: load estimation, siting of PV source, PV sizing and user end energy management are summarized in Table 5:

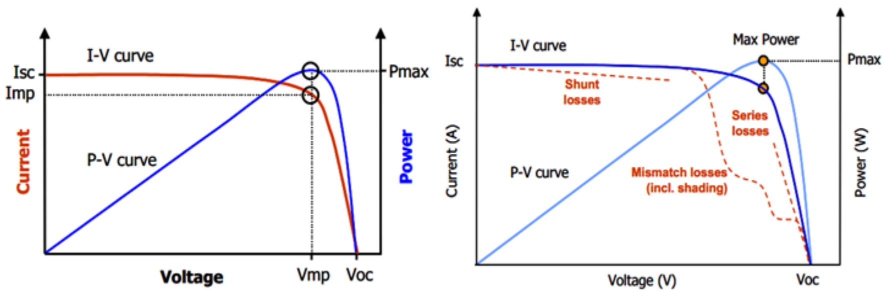

Fig. 4. Variation of I-V Characteristic Curve of PV Cell with Categories of Different Losses

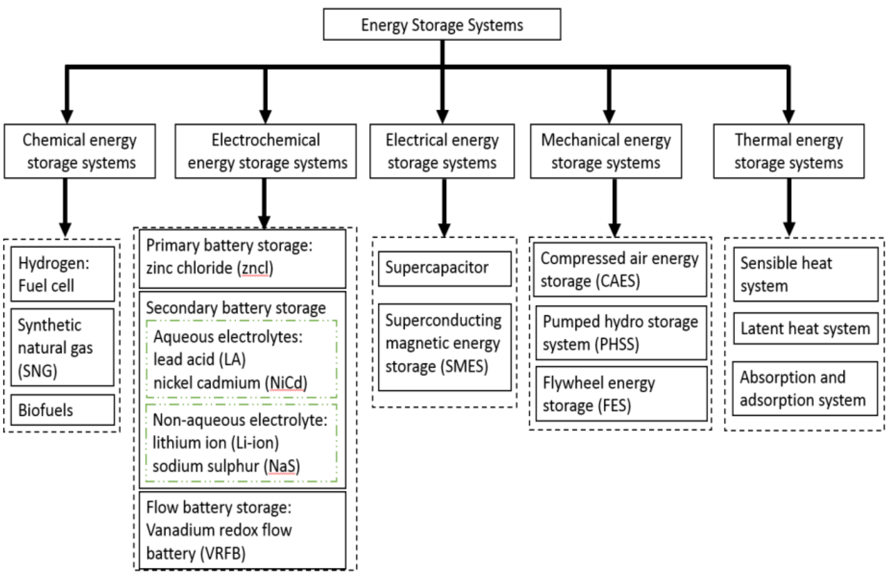

Fig. 5. Energy Storage Systems with examples [28]

Table 2. Rechargeable Battery and Major Characteristics [36,50]

Battery	Power Density (W/Kg)	Energy Efficiency (%)	Energy Density (Wh/kg)	Self-Discharge (%/Month)	Cycle Life (Cycles)
Ni-Cd	140 – 180	60 – 90	40 – 60	10 – 15	500 – 2000
NaS	120 – 150	80 – 90	150	-	2500
Lead-Acid	180	70 – 90	30 – 40	3 – 4	200 – 2000
Li Polymer	3000	70	130 – 200	4 – 8	>1200
Li-Ion	1800	75 – 90	100 – 250	5 -10	500 – 2000
Ni-MH	250 – 1000	70	30 – 80	30	500 – 1000

Table 3. Analysis of artificial intelligent optimization techniques [28,51,52]

Methods	Features	Merits	Demerits
Particle Swamp Optimization (PSO)	PSO mimics bird and fish movement behavior.	Comparatively, it has a fast convergence speed and simple coding.	Not suitable for non-coordinate system problems. It can suffer from partial optimism.
Genetic Algorithm (GE)	GE mirrors different processes of natural evolution such as; selection, inheritance, mutation, etc.	Efficient for finding the global optimum and suitable for complex problems with a great number of parameters.	Convergence speed is slower than most stochastic algorithms. Lack of constant optimization response time.
Ant Colony Algorithm (ACA)	The algorithm is inspired by the foraging behavior of ants in nature. That is, finding the shortest path between their source and their nests.	It is useful for carrying out global search as well as analyzing different optimization problems. It has high convergence speed.	It is a complex process that requires the fine-tuning of its parameters, random initialization and long-term memory space.
Simulated Annealing (SA)	It mirrors the way in which a metal cools and freezes into a minimum energy crystalline structure (the annealing process).	Analyzes non-linear, chaotic and noisy data with many constraints without being trapped in local minima. It is robust technique for determining global optimum.	The quality of the optimal solutions is dependent on the computation time. Fine-tuning of model parameters can be complicated.
Artificial Fish Swamp Algorithm (AFSA)	A class of swamp intelligent optimization Algorithm simulated by the various social behaviors of fish in search of food.	It has rapid convergence, fewer parameters precision and flexibility.	Maintains the benefits of GA but without its drawbacks (crossover and mutation)
Bacterial foraging Algorithm (BFA)	A biologically inspired approach that mirrors bacteria foraging activities to gather the most energy available throughout the search phase.	Both problem size and non-linearity have less effect. Converges to the best solution.	Wide and complex search area.
Harmony Search Algorithm (HAS)	It is a derivative-free, real-parameter optimization algorithm that is inspired by the improvisation process of jazz musicians.	It is free from divergence, suited for discontinuous and continuous functions as well as for discrete and continuous variables.	It seems to adopt a complex problem solving process.

Methods	Features	Merits	Demerits
Biogeography-based optimization (BBO)	Mimics the behaviour of species in nature against time and space by using stochastic and iterative approaches to find the optimal solution.	Its computation time is fast and has good convergence accuracy.	Some of the solutions generated might not be the optimal solution since it is not suitable for selecting the best member within each generation.
Artificial bee colony (ABC) algorithm	This algorithm is inspired by the intelligent foraging behavior of honey bee.	Performs a local and global search. It is useful for optimizing different problems.	Random initialization, as well as fine-tuning of its several parameters, is required.
Hybrid optimization techniques	Developed by combining two or more algorithms.	More robust, quick convergence and offer better calculation accuracy for multi-objective problems.	Hybridization of algorithms results, increased in optimization complexity.

Table 4. Some Software Tools for Renewable Energy Application [53,54,55,56]

Simulation Tools	Relevant Details
MATLAB/Simulink MATPOWER	use matrix based programming languages (C++, Java, and Fortran)
HOMER developed by National Renewable Energy Laboratory (NREL)	Has capacity to simulate the performance of any particular energy system configuration including sensitivity/uncertainty analysis.
CPLEX (IBM, Armonk, NY, USA)	Uses Mathematical programming and constraint programming to model and solve optimization problems. Compatible to C, C++, Java and Python.
TRNSYS based in Madison, WI, USA (latest version, 18)	Very flexible graphically based software for simulation of transient systems in renewable energy systems used to investigate the technical aspect of energy supply.
HOGA – Hybrid Optimization by Genetic Algorithm (Examples, iHOGA and MHOGA) developed in C++	For simulation and optimization of renewable based electricity supply systems.
PVsyst (Photovoltaic Systems), New version PVsyst Version 6.16	Software intended for any type of PV systems analysis and design. It provides detailed financial assessment.
RETscreen (Clean Energy Project Analysis Software: Natural Resources of Canada)	A decision support-software tool which performs comparisons between any given different energy system scenarios.
NREL SAM (National Renewable Energy Laboratory Solar Advisor Model)	Performs parametric analysis, sensitivity analysis, statistical analysis, for effective resource allocation, etc.
ArcGIS, the most powerful GIS software built by Esri - UK	ArcGIS is a geospatial platform (a GIS software) used for working with maps and geographic information. One can compile and sort data with spatial reference to its location. It can be deployed for site suitability analysis and selection.
PVGIS developed by European Commision Joint Research centre (latest version is PVGIS 5)	Free online software for predicting solar resources and PV system performance.

Table 5. Current Literature Survey

Reference	Findings/ Contributions	Optimization Techniques	Mode	Research Gap/ Suggestion for Future
Load Estimation for Remote Area Electrification				
[28]	This study shows that integrated biomass and PV generators can be used for rural electrification and its LCOE can compete with national grid LCOE.	A bottom-up modelling approach was used for generate load profile while Markov chain was used to model the influence of customer habits	Off-grid	No consideration for seasonal weather variation.
[57]	Stochastic bottom-up approach helped in determining the uncertainty of the different customers' energy demands and load profile.	A bottom-up approach applied to estimate the rural community's energy usage, MATLAB program was used to obtain the load profiles.	Off-grid	Research accuracy was affected by the type of load, weather, time of day, seasonality, economic limitations, customers' way of living and other randomness.
[58]	Gender considerations have a significant impact on load profiles. Markov chain process can suitably be used to determine year-to-year load profiles by incorporating the effect of gender and changes in customer habits on estimated load.	Markov chain process was used to model the influence of customer habits and gender on estimated current and future load. MATLAB software helped to generate load profiles.	Off-grid	Regarding load estimation, research was not tested in actual communities through field work studies as part of the process.
[59]	Forecast results showed that the peak load demand varies in the same manner as the Electric Energy Consumption in KWh Per Capita.	Analytical models was developed for estimating the peak load demand, total energy demand, variations in load factor and percentage of population with access to electricity	Off-grid	Study relied on readily available data dataset which is less accurate compared with qualitative data that can be collected on-site.
[60]	The results showed that PV/battery system represents the best renewable energy solution compared to the conventional diesel generator (DG) or PV/DG system.	Bottom-up approach. Ant colony optimization (ACO) and the loss of power supply probability (LPSP) algorithms were used for the search of the optimal hybrid power system.	Off-grid	From the study, the hybrid PV/battery system represents the best renewable energy solution but it does have a high investment cost
[61]	Experiments showed that a	Artificial Neural Networks-ANNs.	Off-grid	Computationally intensive. It does not provide any

Reference	Findings/ Contributions	Optimization Techniques	Mode	Research Gap/ Suggestion for Future
	simple ANN-based prediction model appropriately tuned can outperform other more complex models.	With experimental approach, the entire ANN design space is analyzed and different training strategies applied.		insight about the why and how the result was obtained and this reduces its trustworthiness
[62]	A synthetic load profile was achieved using the top-down approach (measured data).	Top-down stochastic approach. Ward's hierarchical clustering method was used to group users, Markov chain used to develop the synthetic load profile models via the measured data.		Designed for a daily load profile not for a longer time period. Technique makes use of aggregate user data not data considered to be at appliance level. Hence the data are not appropriate.
[63]	The two independent results were comparatively analyzed with the field survey result higher than the estimated value obtained from the energy distribution company by 0.84%.	Study used mathematical approach to determine average monthly and daily energy usage, determine actual annual daily load via field work, interpret and compare results for validation purpose.		It was a mere mathematical analysis with no engineering software deployed for better results.
Optimal Siting of Solar PV Source				
[26]	The study showed the effectiveness of the use of centre of moments approach for identifying the optimal location of central PV source.	The study uses centre of moments for central PV system location, SA for network structure optimization and load flow based parametric analysis for confirming the PV micro-grid structure.	Off-grid	A small capacity single phase PV micro-grids was designed, PV system pre-sizing did not consider the variability of the solar resource over the year, absence of energy management strategy.
[64]	The study determined the most suitable areas for solar PV installation, by analyzing solar irradiance, roads, forest, water bodies, protected areas, town and slope.	AHP determined weighting factors. While ArcGIS prioritized the site to determine the most suitable, GIS was modeled to analyze, store and display spatial data on	Off-grid	There is need to analyze more factors like population concentration and proximity to commercial loads to reduce distance between load centres and power source thereby reducing cost of conductors and power loss.

Reference	Findings/ Contributions	Optimization Techniques	Mode	Research Gap/ Suggestion for Future
		the map.		
[65]	Study showed that Interval Type-2 Fuzzy Analytic Hierarchy Process can be combined with GIS to evaluate the best site for wind farm development using the case study of Nigeria.	A geographic information system-based model for wind farm site selection using interval type-2 fuzzy analytic hierarchy process.	Off-grid	Other factors such as the cost of land and constraints like military base were not considered due to lack of map data. No comparison of the approaches.
[66]	The integration of GIS and MCDA has emerged as a very useful technique to deal with rich geographical info data and to manipulate existing criteria toward selecting the best site for solar power plants.	Applied GIS and MCDA. An analytical hierarchy technique was applied to weigh the criteria and compute a land suitability index to evaluate potential sites. ArcGIS was deployed to calculate the solar insolation across the study area.	Off-grid	Average temp is interpolated using the spline tool in ArcGIS. Considering a small number of points for the temp interpolation process can reduce accuracy. Need for more decision criteria example, population growth to enrich results.
[67]	Selection of optimal locations for off-grid solar PV microgrid projects is influenced by: climatology, orography, technical/location, social and institutional criteria. Fuzzy-AHP eliminates the imprecise judgments of experts.	Off-grid solar energy planning based on a GIS and Boolean logic, Fuzzy logic, and Analytic Hierarchy Process Multi-criteria Decision-Making methods (AHP-MCDA)	Off-grid	To further strengthen the methodology, appropriate multiple criteria and constraints related to other RES-based site selection problems such as wind, biomass, geothermal, should be considered
[68]	The reliability of criteria that help decision makers in planning renewable solar energy development including siting can be tested and proven.	Deployed MCDA to form expert groups, a questionnaire and compile a scale of criteria. AHP was used to assign the weights to each evaluation criteria.		The weakness of this method is the lack of empirical evidence of the influence of a given factor on the final result of decision-making, which is why the value of separate factor is judged by experts.
PV Microgrid Sizing for Remote Area Electrification				
[6]	The results yielded a	MILP was use to	Off-grid	Cost of electricity from off-grid

Reference	Findings/ Contributions	Optimization Techniques	Mode	Research Gap/ Suggestion for Future
	reliable, accurate and less expensive PV microgrid with a faster convergence.	optimally size the PV micro-grid and —Density Based Spatial Clustering of Applications with Noise (DBSCAN) algorithm helped to aggregate load and meteorological data		systems incorporating storage was shown to be higher than that supplied by the main grid. Absence of field work and energy management system.
[69]	The results revealed more PV power can be generated in the dry season compared to the wet season.	A size optimization model was developed on the basis of meta-heuristic PSO technique. A fuzzy-logic EMS was developed for power control and energy storage.	Off-grid	The membership functions of the variables and the fuzzy logic rules were constructed on the basis of the operators' knowledge not using PSO or any other optimization algorithm.
[70]	Involvement of private energy providers in the deployment of solar PV in rural communities is more effective than the sole use of government agencies or contractors.	Multiple methods of observation, interviews, discussions with relevant stakeholders and evaluation of case studies.	Off-grid	Difficulties in getting government officials to grant interviews and the dearth of critical information on government agencies' websites reduce the richness and depth of the results.
[5]	A grid-connected system is more reliable and cost-effective compared to a stand-alone.	Discrete Harmony Search (DHS) algorithm was adopted to optimize the system.	On-grid	Absence of demand-side management, power quality and stability.
[71]	The results highlight the benefits of the developed tool and provide guidelines regarding Ecuador's Amazon region electrification.	MILP was applied to determine the details of the electrification design in order to minimize the project cost.	Off-grid	The work did not account for uncertainty in the amount of PV energy collected which depends on meteorological factors and user's energy demands.
[72]	Decreased total operating expenses while preserving the	Non-linear Programming	Off-grid	Systematic battery storage was not examined. The cost of emissions for distributed

Reference	Findings/ Contributions	Optimization Techniques	Mode	Research Gap/ Suggestion for Future
	safe operation of the standalone.			biomass generation was not evaluated too.
[73]	Easy implementation, enhanced power profile quality of the grid.	Artificial Intelligence (Fuzzy logic)	On-grid	Only the battery charger/grid connected inverter is controlled. Battery degradation was not evaluated.
[74]	Batteries used to stabilize and permit PV to run at a constant and stable output power. Energy management strategy for PV.	Dynamic Programming	Off-grid & on-grid	Battery degradation and life time prediction were not evaluated.
End User Energy Management System (EEMS)				
[15]	Displayed a potential for energy management at the household level by cutting off electrical appliances which are not being used or on standby.	Genetic algorithm (GA) was used on smart meter-like data to optimize the energy consumption of households for 24 hours on a weekday and weekend.	Off-grid	Use of simulated data for the modeling which might not always be the case in a real life scenario. Field work required.
[75]	The present survey provides a comprehensive update on HEMS literature, focusing on: appliance scheduling, constrained scheduling problem.	A thorough review on HEMSs, along with household appliance management, uncertainties in HEMSs' decision-making and performance metrics	Off-grid	Further research on automatic and dynamic context discovery, self-adaptation, self-re-configuration, artificial awareness, uncertainty modeling are needed.
[76]	Simulations showed that EMS enables considerable savings. The cumulative effect of these savings has a notable impact on PV system profitability.	A multi-objective optimization algorithm based on PSO was developed to optimize the HEMS.	Off-grid	Large scale implementation of HEMS to decarbonize residential energy sector needed. Concerns are; modeling complexity and forecasting uncertainty.
[77]	Study reduces the consumer electricity bill via energy consumption scheduling of two controllable home appliances (AC and a washing machine) while maintaining	Q-learning home energy management algorithm integrated with the artificial neural network (ANN) Model.	Off-grid	Integration of advanced neural network models such as recurrent neural networks and long short-term memory to improve the prediction accuracy of the indoor temperature.

Reference	Findings/ Contributions	Optimization Techniques	Mode	Research Gap/ Suggestion for Future
	consumer comfort level and appliance operation characteristics			
[78]	Through the optimization of the usage of PV energy production, the study reduces energy consumption and ensures user's comfort and load shifting.	Deep reinforcement learning (DRL) algorithm for indoor and domestic hot water temperature control.	Off-grid	Uncertainty of PV plants was not considered. A different approach to get the user's set-point preferences could be applied. Study can be extended to other locations with different PV production patterns.
[79]	Incorporated the outdoor weather conditions prediction and a day ahead timetable of the heat-pump thermostat in the HEMS forecasting model.	Batch Reinforcement Learning technique fitted Q-iteration to incorporate a forecast of the exogenous data.	Off-grid	More Appliances can be considered. Future research can deploy the presented algorithms in a realistic laboratory environment.
[80]	Fuzzy logic is proposed to enable off-grid operation for HEMS which is connected with different DERs such as fuel cells, batteries, solar panels, and wind turbines.	Fuzzy logic controller was designed for the energy management algorithm. Proposed system was tested in MATLAB Simulink	Off-grid	The Operating parameters of all household appliances are assumed to be fixed
[81]	Results showed that the BBSA schedule controller is better than the BPSO schedule controller in terms of reducing the energy consumption of home appliances at weekday and weekend without affecting the comfort level of the customers.	New binary backtracking search algorithm (BBSA) to manage the energy consumption. Results compared with BPSO	Off-grid	All home Appliances were considered to be controllable loads.
[82]	Appliance Net was proposed to recognize the energy consumption patterns of household appliances connected to smart plugs.	Study deployed a multi-layer, feed-forward neural network to classify home appliances which are non-linear.	Off-grid	More kinds of appliances can be considered

9. FUTURE DIRECTIONS

- PV system sizing and Load model developed should be modified to capture the variability of solar resource over the year. There is dare need to investigate the effect of changes in the socio-economic factors of a community and/or customer habits/behavior on estimated load using suitable statistical or AI technique to be able to provide a way of measuring and estimating load growth over time. Accurate load profile will facilitate proper microgrid planning and design.
- Well planned field study in the area of load estimation through the creation of appropriate questionnaires to be used in the electrical survey is very important. This would produce real data from an existing electrical network for simulations to fix the problem of inaccuracy in load estimation and ensure reliability of results.
- In PV system siting, aside factors such as; solar irradiance, roads, forest, water bodies, protected areas, town and slope analyzed using GIS and rank using AHP and similar tools, there is need to analyze more factors like population concentration and proximity to commercial loads including optimization of network structure to reduce distance between load centres and power source thereby reducing cost of conductors and power loss.
- Attention should be paid on investigation into end-user energy management (EEMS) based on a combination of direct and indirect load control strategy. This should put into consideration the nature of the communities and customers being served, as the success of EEMS largely depends on the percentage of controllable loads. More research is required to improve the resilience of EEMS to cyber-attack by developing designs with less vulnerability. Threats such as; systems' failure, smart meters' data corruption, infection by malware and unauthorized access, show the necessity for research towards threat and risk modeling, intrusion detection and prevention techniques.

10. CONCLUSION

In a nutshell, the literature presented has indicated the trends, directions and possible inclination of research into PV based micro-grid for rural electrification in Nigeria. The concept of PV Microgrids in the context of Nigeria's rural communities, fundamental issues in PV electrification generation and energy storage systems have been reviewed. PV based micro-grid for rural electrification has evolved and advanced thereby creating opportunities with regards to the use of smart and highly intelligent systems, particularly the application of artificial intelligence (AI) to address the current evolving challenges and opportunities in solar photovoltaic systems' sizing, siting, load estimation and end user energy management. Consequently this review has equally paid specific attention to prominent AI microgrids optimization techniques including their strengths and weaknesses. Consistent with trend, a comprehensive review of key and modern optimization strategies on latest research works involving PV microgrids sizing, siting, load estimation and end user energy management equally formed the focus of the study. For the purpose of ensuring sustainability of rural electrification projects, accuracy in load estimation, optimal sizing of PV microgrids, optimal site selection to reduce cost and power loss, and prevention of energy wastage at the user end, this review has identified future research directions and potential of PV based microgrids for rural electrification. In terms of limitation, only studies written in the English language were included and also review was restricted to mostly studies published in the last 15 years.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as; Large Language Models (ChatGPT, COPILOT, metaAI and so on etc.) and text-to-image generators have been used during writing or editing of this manuscript.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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