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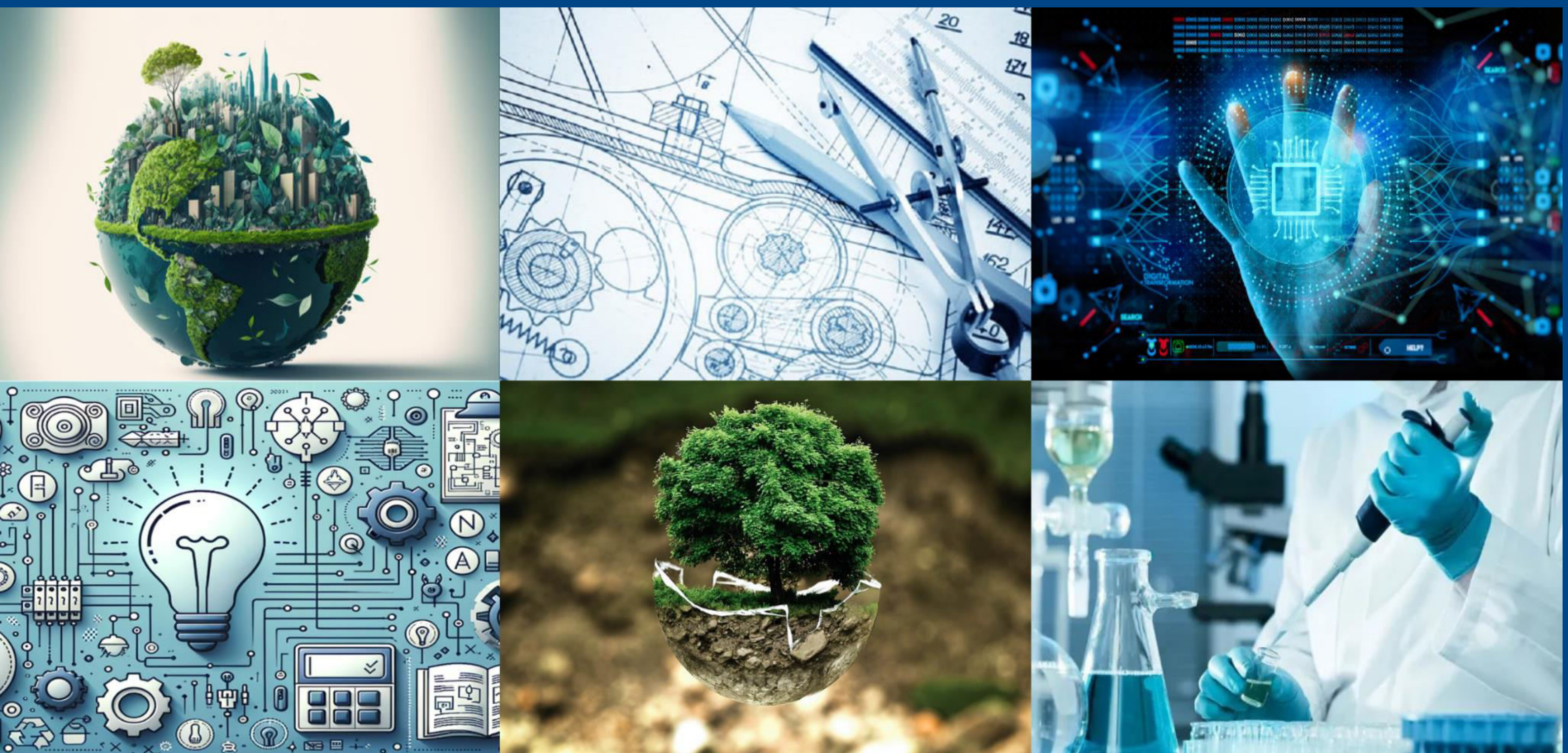

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A Comprehensive Review of Standalone Solar PV-Based Rural Microgrids: Design, Optimization, Control Strategies, and Energy Management

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ABSTRACT: It is not possible to provide cheap and reliable electricity to distant areas because it's expensive and hard to do. In recent years, independent Solar Photovoltaic (PV)-powered microgrids have become an option, using locally sourced renewable energy and battery storage to keep the lights on. [3, 11, 15] Researchers have studied ways to improve the design of microgrids, how big they should be, how to manage energy, and how to control them so that they can work better, and cost less and have less impact on the environment [4, 5, 13]. This paper looks into all the recent advances in standalone solar PV-based rural microgrids. There are a number of optimization tools and algorithms that are compared for their techno-economic feasibility and use in rural electrification: HOMER, MATLAB/Simulink, MILP, Genetic Algorithm, Particle Swarm Optimization, Dandelion Optimizer. The studies reviewed show us what we still don't know, what we still need to study, and what we can do to make our rural microgrids more reliable, affordable, and sustainable.

KEYWORDS: Standalone Solar PV Microgrid, Rural Electrification, Battery Energy Storage System (BESS), Energy Management System (EMS), Microgrid Optimization, Control Strategies, Renewable Energy, Techno-Economic Analysis.

I. INTRODUCTION

Electricity is the key to a better education, health, agriculture, and economy. However, electrifying remote and rural areas is still a big challenge because it costs a lot to expand the grid, it's hard to reach certain areas, and not many people live there. One of the most promising renewable energy technologies is standalone Solar Photovoltaic (PV)-based microgrids because they provide clean, decentralized, and sustainable electricity. The integration of Battery Energy Storage Systems (BESS) makes the system even more reliable by covering the inconsistency of solar energy and power outage during the night. [1, 11, 19] In the past ten years, a lot of research has focused on how to improve the design, size, energy management, control systems, and techno-economic performance of standalone Solar PV-based microgrids for rural electrification [4, 5, 13]. Different techniques like HOMER, MATLAB/Simulink, MILP, GA, PSO, and Dandelion Optimizer have been used to create economical and reliable microgrids under different scenarios. In addition, there have been control strategies and energy management models proposed to improve voltage control, power sharing, battery use, and system stability [7, 9, 18].

This paper will be a thematic review of standalone Solar PV-based rural microgrids by categorizing the literature into four main research areas: design, optimization, control strategies, and energy management. I compare these studies to see what has changed, what we still don't know, and what we need to do next to build reliable, affordable, and sustainable rural microgrids.

II. LITERATURE REVIEW

A. Design of Standalone Solar PV-Based Rural Microgrids

Designing standalone Solar Photovoltaic (PV)-based rural microgrids plays an essential role in delivering a reliable, cost-effective, and sustainable power source to remote communities where extending the grid becomes an unrealistic option. The typical standalone microgrid includes Solar PV panels, BESS, power electronics, and loads, and sometimes supplementary power sources (e.g., diesel generator, wind turbine, micro-hydro system, etc.) are integrated to increase the system reliability in varying environmental conditions [3, 11, 16, 19]. The choice of system architecture mainly depends on renewable sources availability, the characteristics of load profile, and geographical and economic aspects.

Recent research shows that Solar PV-BESS configuration is the most popular architecture for rural electrification owing to its simplicity, minimal maintenance, and decreasing cost of installation [11, 15]. Nevertheless, hybrid architectures including Solar PV and other renewable sources such as wind power, hydro power, or diesel generator show an increase in reliability of system owing to reduced solar intermittency and increased power availability in adverse weather conditions [3, 16, 19]. In addition, the use of several energy sources reduces battery stress.

Optimal design of the microgrid starts from precise estimation of the load profile of the community since the correct size of PV modules, battery, and power conversion system is dependent on the size of load [6, 15]. Moreover, many researchers have pointed out that incorrect sizing leads to oversizing and high initial cost of installation, or undersizing and unreliable operation of the system owing to the lack of sufficient power production and storage [5, 15]. Therefore, a comprehensive assessment of daily energy consumption, seasonal solar insolation, and the forecasted growth in load is required for microgrid design. In addition to the problem of component selection, recent research emphasizes the importance of solar energy resource assessment and evaluation of the local environment when designing a microgrid. Reliable solar resource assessment results in more accurate forecasting of the energy production and better performance of the system, especially in geographically diverse rural areas [17]. Moreover, modular system architectures get much attention because of the possibility of increasing the capacity of the system due to electricity demand growth in rural communities [6, 11].

Generally, based on the review of the literature, it can be stated that the optimal design of standalone Solar PV-based microgrid presupposes the combination of technical reliability, economic feasibility, and renewable energy utilization. Proper system configuration, correct sizing of components, and taking into account local energy sources become important criteria for microgrids' successful implementation [3, 5, 11, 15].

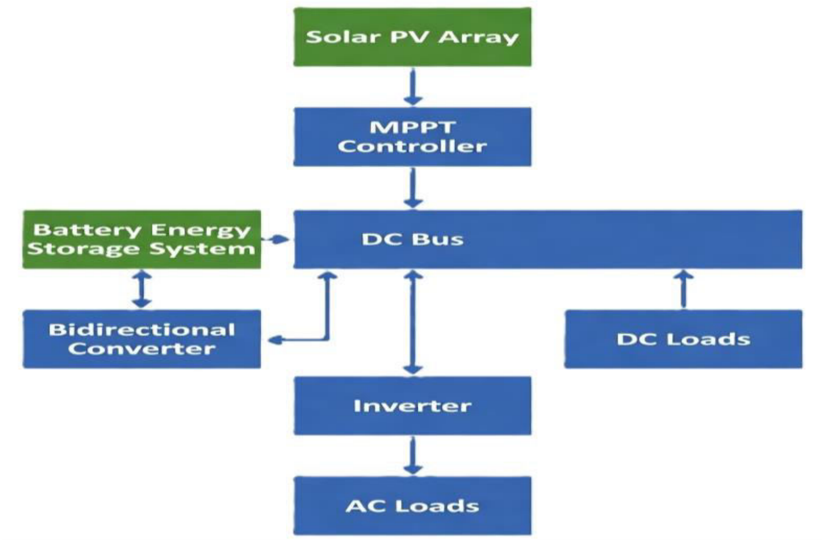

Fig. 1. General architecture of a standalone Solar PV-based rural microgrid.

B. Optimization of Standalone Solar PV-Based Rural Microgrids

The key to successful implementation of standalone Solar PV-based rural microgrids is a well-optimized design ensuring proper balance between technical, economic, and performance requirements [5, 10, 13]. Since renewable energy sources are characterized by intermittency, an optimized design is required to establish the correct capacity of PV systems, battery storage, and other elements of microgrids, as well as to minimize the cost associated with their operation throughout the entire lifetime of the project [5, 10, 13]. The most common objectives stated in the literature include minimization of Net Present Cost (NPC), Cost of Energy (COE), improvement of the amount of used renewable energy, and reliability of power supply for rural areas [10, 13, 15]. Different optimization tools and algorithms were applied to find the optimal design of standalone microgrids depending on climatic and load conditions. HOMER is widely used owing to its ability to perform a techno-economic evaluation of several system designs simultaneously based on economic, technical, and environmental parameters [3, 10, 15]. In its turn,

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MATLAB/Simulink is applied to validate the performance of the optimized microgrid through simulation of the process of power generation and distribution [3, 13]. Finally, new optimization algorithms, including MILP, Genetic Algorithm (GA), Particle Swarm Optimization (PSO), and Dandelion Optimizer, show improved convergence properties compared to traditional methods [5, 13]. A techno-economic evaluation is also an important step of the optimization process. Almost all examined articles use NPC, COE, Levelized Cost of Energy (LCOE), operating cost, renewable energy fraction, and battery replacement cost to assess the economic efficiency of various designs [5, 10, 13, 14, 15]. Moreover, sensitivity analyses in terms of solar irradiation, fuel prices, and load changes have been conducted to ensure the robustness of the optimized design in real-world scenarios [5, 10]. In general, the reviewed literature suggests that optimization greatly increases the economic efficiency and performance reliability of standalone Solar PV-based rural microgrids. The combination of modern optimization algorithms and techno-economic evaluation makes it possible to develop sustainable cost-effective solutions for rural electrification [5, 10, 13, 15].

Table 2. Comparison of Optimization Techniques

Ref	Method	Software	Objective	Performance Index
[5]	Dandelion Optimizer	MATLAB	Cost minimization	NPC, COE
[10]	HOMER	HOMER	Feasibility	NPC
[13]	MILP	MATLAB	EMS Planning	Cost
[14]	Optimal Dispatch	MATLAB	Dispatch	Efficiency
[15]	HOMER	HOMER	Component sizing	COE

C. Control Strategies for Standalone Solar PV-Based Rural Microgrids

Control techniques are needed to ensure the steady and reliable operation of standalone Solar PV-based rural microgrids under continuously changing conditions related to the power generation and loads. As solar power generation is characterized by an intrinsic intermittency, special control techniques should be applied in order to ensure the regulation of voltage and power flows, proper functioning of batteries, and continuous power supply to the connected loads [7, 9, 18]. In addition, an appropriate control strategy helps to improve the performance of the whole system through increased efficiency, decreased power fluctuations and other benefits. The reviewed researches deal mainly with such aspects of control strategies as voltage regulation, power-sharing methods, converter control load and battery charge/discharge control in order to ensure stable system operation [7, 18]. Modern techniques of converter control are actively used for the DC bus voltage stabilization and power quality improvement under dynamic loading conditions, whereas adaptive control methods allow for obtaining fast responses to any sudden changes in the solar power generation and consumer demands [7, 18]. Moreover, there is evidence proving that the coordinated control of the PV array, battery storage system and power converters increases the energy utilization and decreases unnecessary battery cycles [9, 13]. Moreover, many research papers state that control strategies are critical factors influencing the reliability of systems because of the decreased voltage deviation, load sharing, ng and utilization of renewable energy sources [7, 9, 18]. At the same time, when used in combination with intelligent energy management systems, control approaches provide better coordination of all system components and lead to improved stability and extended battery lifetime [9, 13]. It can be concluded from the reviewed literature that control strategies play an important role in ensuring efficient, reliable, and sustainable operations of standalone Solar PV-based rural microgrids [7, 9, 13, 18].

Table 3. Comparison of Control Strategies in Standalone Solar PV-Based Rural Microgrids

Ref	Control Strategy	Main Objective	Key Outcome
[7]	Adaptive Filter Control	Voltage and power regulation	Improved dynamic performance
[9]	Coordinated Control with EMS	Battery and power management	Enhanced energy utilization
[13]	Integrated EMS-Based Control	System coordination	Improved reliability and efficiency
[18]	Voltage Control	DC bus voltage regulation	Better voltage stability and power quality

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D. Energy Management in Standalone Solar PV-Based Rural Microgrids

Effective energy management is an important part of the efficient and economically feasible operation of Solar PV-based rural standalone microgrids due to its ability to coordinate power generation and storage and electricity load demands at all times when the system conditions change [4, 9, 13]. The appropriate Energy Management System determines the proper solar energy utilization, controls the charging and discharging processes of the batteries, and provides continuous electricity supply with minimum energy losses and reduced operational costs [4, 13]. In addition, with the growing share of renewables, energy management becomes an indispensable tool for increasing the reliability of the system and utilizing local energy sources to the maximum extent possible. Among the different approaches used in the examined papers, there are rule-based control strategies, cost-oriented energy management, and optimization-based scheduling technique which help increase the operational efficiency of standalone microgrids [4, 9, 13]. In particular, all of these strategies focus on the prioritization of solar PV electricity generation as well as rational management of the battery energy to avoid unnecessary charging of the batteries, increase their lifespan, and limit the usage of additional energy sources [1, 4, 9]. Moreover, integration of energy management techniques leads to better coordination of system elements and increases power availability, reduces operational costs, and promotes renewable energy penetration [13, 18]. In addition, recently developed hybrid energy storage systems with more sophisticated energy management systems showed better flexibility of battery behaviour under fluctuating load and weather conditions [1]. Therefore, energy management is considered to be an integral part of any standalone Solar PV-based rural microgrid and is among the most important technologies that allow long-lasting rural electrification [1, 4, 9, 13, 18].

Table 4. Comparison of Energy Management Strategies

Ref	EMS Technique	Primary Objective	Key Contribution
[1]	Hybrid Energy Storage Management	Improve battery lifetime	Enhanced storage utilization
[4]	Cost-Driven EMS	Reduce operating cost	Economic power scheduling
[9]	Rule-Based EMS	Energy balance	Efficient PV–battery coordination
[13]	Optimization-Based EMS	Optimal resource allocation	Improved system reliability
[18]	Voltage and EMS Coordination	Stable DC bus operation	Enhanced voltage regulation

III. COMPARATIVE ANALYSIS OF REVIEWED STUDIES

The reviewed literature reflects major breakthroughs in the design, optimization, control, and energy management of standalone Solar PV-based rural microgrids for rural electrification. Despite the similarities in the objectives of improving system reliability and economics, different microgrid configurations, optimization methods, control techniques, and energy management approaches have been studied [3, 19]. Standalone Solar PV-battery-based microgrid systems are the most common configurations due to their simplicity and applicability to remote areas, while hybrid microgrids with wind, hydro, diesel, or hydrogen energy storage systems are more reliable in varying environmental conditions [1, 3, 12, 16, 19]. Optimization-based research is mainly concentrated on NPC minimization, COE minimization, and reduction of battery replacement costs along with the reliable supply of electric power. The HOMER tool and MATLAB/Simulink are the most used optimization tools, while more advanced methods like MILP and Dandelion Optimizer are utilized in recent studies to enhance the techno-economic performance of the system [5, 10, 13, 15]. In addition, the implementation of intelligent energy management and control techniques resulted in improvements in the voltage regulation process, battery performance, renewable energy integration, and general system stability [4, 7, 9, 13, 18]. Thus, it can be stated that the combination of the optimal system design and intelligent energy management/control results in the enhancement of the techno-economic performance of standalone Solar PV-based rural microgrids. However, additional research is needed to propose an integrated adaptive framework that will be able to meet the increasing energy demands of rural areas.

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Table 5. Comparative Analysis of Reviewed Studies

Ref	System Configuration	Optimization Technique	Control / EMS	Major Contribution	Limitation
[1]	PV–BESS (HESS)	—	HESS Management	Improved battery lifetime	High implementation complexity
[2]	Rural Microgrid	—	Demand Analysis	User-centric energy planning	Limited technical analysis
[3]	PV–Diesel–Battery	HOMER	Basic Control	Techno-economic assessment	Diesel dependency
[4]	DC Microgrid	Cost Optimization	Cost-Driven EMS	Reduced operating cost	DC system only
[5]	Standalone PV	Dandelion Optimizer	—	Optimal component sizing	Limited practical validation
[6]	Solar Home System	Design Methodology	—	Improved rural electrification planning	No optimization algorithm
[7]	PV–Battery	Adaptive Filter	Advanced Control	Better dynamic response	Grid-interactive focus
[8]	DC Microgrid	Loss Analysis	—	Distribution loss reduction	No EMS consideration
[9]	DC Community Grid	—	Rule-Based EMS	Efficient battery utilization	Limited optimization
[10]	Rural Microgrid	HOMER	—	Grid extension feasibility	Case-specific analysis
[11]	PV–Battery	—	Basic Control	Sustainable rural electrification	Limited optimization
[12]	PV–RHFC	Multi-objective Optimization	EMS	Hydrogen integration	Higher system cost
[13]	PV Microgrid	MILP	Optimization-Based EMS	Integrated planning and EMS	Computational complexity
[14]	Hybrid Microgrid	Optimal Dispatch	Dispatch Control	Improved power allocation	Case study validation
[15]	PV–BESS	HOMER	—	Optimal sizing	Residential application only
[16]	PV–Hydro–Battery	Design Optimization	—	Improved supply reliability	Site dependency
[17]	Solar Resource	Resource Assessment	—	Accurate solar potential estimation	No system optimization
[18]	DC Microgrid	—	Voltage Control + EMS	Improved voltage regulation	DC architecture only
[19]	PV–Wind–Battery	Design Optimization	Basic Control	High renewable penetration	Weather dependency

IV. RESEARCH GAPS AND FUTURE PERSPECTIVES

As it is visible from the analyzed papers, much attention has been devoted to standalone Solar PV-based rural microgrids development in terms of system design and optimization. However, several essential research gaps are yet to be covered. First, although a considerable number of papers discuss aspects of the mentioned microgrids' design and optimization, relatively few studies try to integrate design, optimization, control, and energy management in an integrated approach [5, 10, 13]. Second, despite the widespread use of simulation-based validation, there are not

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enough research works that focus on performance assessment under real rural conditions [3, 5, 15]. BESS is one of the key problems in standalone microgrids. Although many researchers have found approaches to improving battery utilization and extending its service life, battery degradation problem, battery replacement costs, and accurate prediction of long-term performance of batteries require additional study [1, 4, 9]. Similarly, many proposed control and energy management approaches are applicable to pre-defined operating modes and fail to provide satisfactory results under the conditions of fluctuations in renewable power production and community electricity demand [7, 13, 18]. Future research should address the development of integrated frameworks for the simultaneous consideration of optimization, control, and energy management with regards to technical, economic, and operation-related objectives. Moreover, more experimental research and field demonstrations are needed for practical verification of proposed methods. Further research may also be conducted in the areas of hybrid energy storage, intelligent control algorithms, and adaptive energy management approaches in order to increase the reliability and operational flexibility of the systems [1, 12, 13]. Design and planning approaches for various geographical and socio-economic conditions should also be elaborated [2, 10, 17].

V. CONCLUSION

Sole Solar Photovoltaic (PV)-based rural microgrids represent an efficient and sustainable approach towards rural electrification, as they can be successfully utilized in remote locations where it is hard from economic and technical perspectives to connect the community to a standard power grid. This review analyzed recent developments in standalone Solar PV-based rural microgrids' design, optimization, control, and energy management approaches according to the selected literature sources. According to the studies reviewed herein, a good system design and components optimization, as well as proper Battery Energy Storage System (BESS) integration, can improve the system's reliability, efficiency, and economy [3, 11, 15]. At the same time, it has been shown that the application of intelligent optimization and energy management techniques plays a significant role in improving the renewable energy utilization level, decreasing system costs, and ensuring its stability under different operating conditions [4, 5, 13]. Despite the progress that has already been achieved, issues associated with BESS lifetime, integrated system development, and practical implementation still require attention [1, 12, 13].

On the whole, the utilization of standalone Solar PV-based rural microgrids can be considered as a good way of achieving sustainable rural electrification due to improved energy access and increased utilization of clean energy sources.

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