

Environmental Hybrid Optimization Of Renewable Energy Systems (HOMER) For Off-Grid Rural Electrification

Kannan Kandavelu¹, Paramaguru. G², Anbuhezian Ashokan³, Silambarasan Rajendran⁴

¹Department of Electrical and Electronics Engineering, Annapoorana Engineering College (Autonomous), Seeragapadi, Salem, 636308, Tamil Nadu, India.

²Department of Mechanical Engineering, Tagore Institute of Engineering and Technology, Deviyakurichi, 636112, Tamil Nadu, India.

³Department of Civil Engineering, Annapoorana Engineering College (Autonomous), Seeragapadi, Salem, 636308, Tamil Nadu, India.

⁴Department of Mechanical Engineering, Annapoorana Engineering College (Autonomous), Seeragapadi, Salem, 636308, Tamil Nadu, India. ⁴Department of Mechanical Engineering, Saveetha School of Engineering, Saveetha Institute of Medical and Technical Sciences, Chennai, Tamil Nadu, India.

Abstract

This study investigates the hybrid renewable energy systems (HRES) to meet the energy needs of off-grid rural communities using the HOMER simulation software. The biomass is ensuring both energy reliability and environmental sustainability. A representative rural load profile and locally available renewable resources are considered to evaluate different system configurations. Simulation results reveal that a properly sized hybrid system significantly reduces emissions while providing cost-effective electricity.

Keywords: HOMER, Off-grid Electrification, Optimization, Rural Development, Energy Sustainability,

1. INTRODUCTION

In many cases, extending the national grid to these areas is economically unfeasible due to geographical challenges, low population density, and high infrastructure costs [1]. Consequently, off-grid electrification using bridge the energy access gap and biomass with energy storage and backup generators, offer a promising solution for rural electrification [2]. These systems overcoming the intermittency and variability of individual renewable sources [3]. It requires careful analysis of resource availability, load demand, component sizing, economic feasibility, and environmental impact. It helps identify the most cost-effective configuration while considering technical and operational constraints [4]. Over the past few decades, rural electrification has been a key focus area for sustainable development initiatives globally. Numerous studies providing electricity to off-grid rural communities using various technologies, including grid extension, standalone systems, and hybrid renewable energy systems (HRES) [5]. Barnes and Floor (1996) examined the economic justification of rural electrification projects and emphasized that electrification alone does not guarantee economic growth unless accompanied by complementary development programs [6]. Tenenbaum et al. (2014) provided a comprehensive guide on mini-grid design and emphasized in promote decentralized energy solutions. Recent research has increasingly focused on renewable-based hybrid systems as viable alternatives to traditional diesel generators in rural areas [7]. Kellogg et al. (1998) were among the first to propose rural application, highlighting the trade-offs between cost and reliability [8].

Sen and Bhattacharyya (2014) conducted a techno-economic evaluation of solar-diesel hybrid systems for Indian villages, concluding that such systems are cost-effective under the right subsidy and policy environment [9]. Mandelli et al. (2016) reviewed global trends in rural electrification using off-grid systems and emphasized the importance of site-specific solutions based on energy demand and local resource availability [10]. In a similar vein, Nfah et al. (2008) analyzed the feasibility of micro-hydro, PV, and biomass-based hybrid systems in Cameroon and found that integrated solutions provided the best balance between cost and sustainability [11]. Mahmoud and Ibrik (2006) modeled PV and diesel hybrid systems in remote areas of Palestine using HOMER software, and their results demonstrated significant improvements in fuel savings and emissions reduction [12]. More recently, Mulugetta et al. (2019) analyzed decentralized energy systems for sub-Saharan Africa, emphasizing the role of hybrid systems in achieving universal energy access by 2030 [13]. However, most of the literature stresses the importance of customized system design that aligns with environmental conditions of the target area. With the evolution

of simulation tools like HOMER, accurate modeling and optimization of these systems have become more accessible, enabling researchers and policymakers to make data-driven decisions.

2. METHODOLOGY OF RESEARCH

The methodology involves designing and optimizing a HRES using HOMER software. The electrical load profile of the community is estimated by analyzing daily and seasonal energy consumption patterns for households, schools, health centers, and small businesses. Meteorological feedstock is obtained from reliable sources such as NASA or local weather databases. Technical and economic parameters for system components—solar, battery banks, and inverters—are defined using manufacturer specifications and literature values. These inputs are entered into HOMER, which simulates various system combinations and performs an optimization. This methodology ensures practical assessment of hybrid energy for rural electrification (Figure 1).

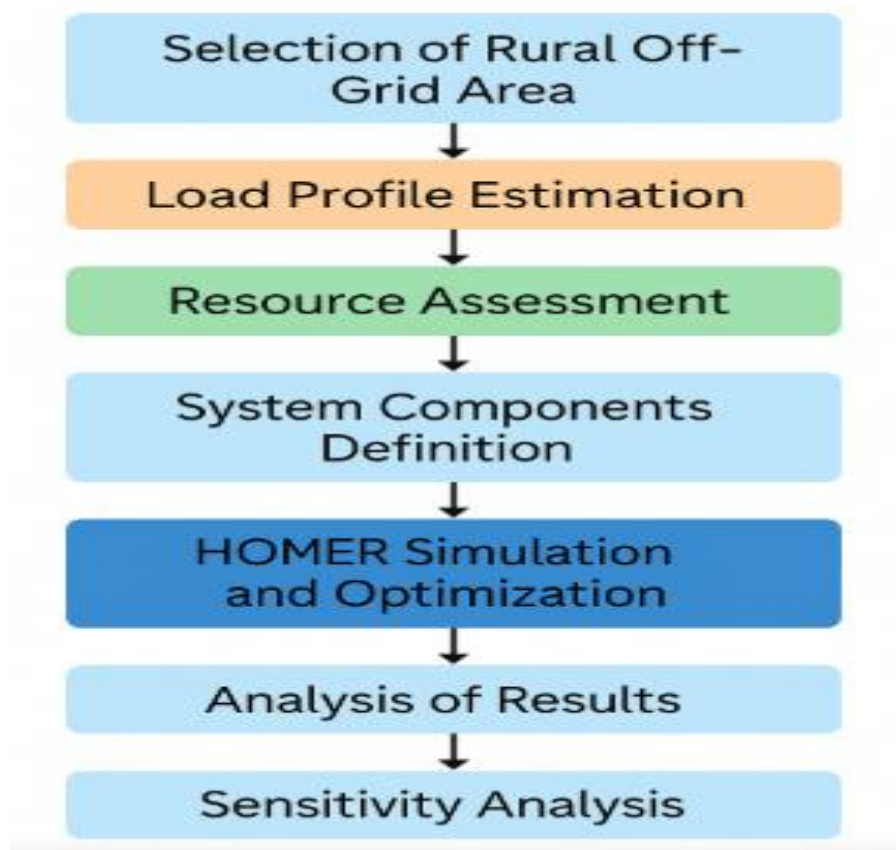


Figure 1. Methodology of Research

2.1 Capabilities of HOMER

HOMER has evolved from a research prototype into commercial-grade software used globally by researchers, planners, and energy developers. Its key capabilities include:

- **Simulation of Multiple Configurations**

HOMER simulates thousands of system configurations using different combinations .

- **Optimization Based on Economic Criteria**

The software determines the optimal system design by minimizing fuel consumption, while considering user-defined constraints and priorities.

- **Techno-Economic and Environmental Assessment**

HOMER computes energy production, component operation, emissions (CO₂, CO, NO_x, etc.), and unmet load, making it suitable for evaluating environmental sustainability alongside cost-effectiveness.

- **Grid and Off-Grid System Design**

HOMER can model grid-tied systems, off-grid microgrids, or isolated standalone systems, supporting a wide range of use cases from rural electrification to industrial applications.

- **User-Friendly Interface**

Its graphical interface and extensive component library make it accessible to both beginners and experts in renewable energy planning.

2.2 Applications of HOMER in Research and Practice

HOMER has been extensively applied in academic research, feasibility studies, and commercial project planning across the world. Key applications include:

- **Off-Grid Rural Electrification**

HOMER is widely used to design hybrid systems (PV/Wind/Diesel/Biomass) to electrify .

- **Microgrid Design**

Utilities and private developers use HOMER to plan islanded or grid-connected microgrids with renewable integration and storage.

- **Renewable Energy Integration**

Studies use HOMER to assess the impacts of adding renewable sources to diesel-based or grid-based systems in order to reduce emissions and operational costs.

- **Disaster Resilience and Emergency Power Systems**

HOMER helps plan backup power systems for hospitals, emergency shelters, and military bases using renewable energy sources to improve resilience and reliability.

- **Comparative Techno-Economic Studies**

Researchers use HOMER to compare configurations based on performance, reliability, and environmental benefits.

3. Schematic Description of a HRES

Turbines serve converting sunlight and wind energy into electrical power. Due to their intermittent nature, a biomass generator is included to provide stable and dispatch able renewable energy using organic waste materials [14].A centralized inverter/controller manages the power flow from all sources, prioritizing renewable energy first, followed by storage, and finally diesel generation. The power bus consolidates the inputs and directs electricity to meet the load requirements. This configuration minimizes fuel consumption, reduces environmental emissions, and enhances the sustainability and economic viability of rural electrification (Figure 2).

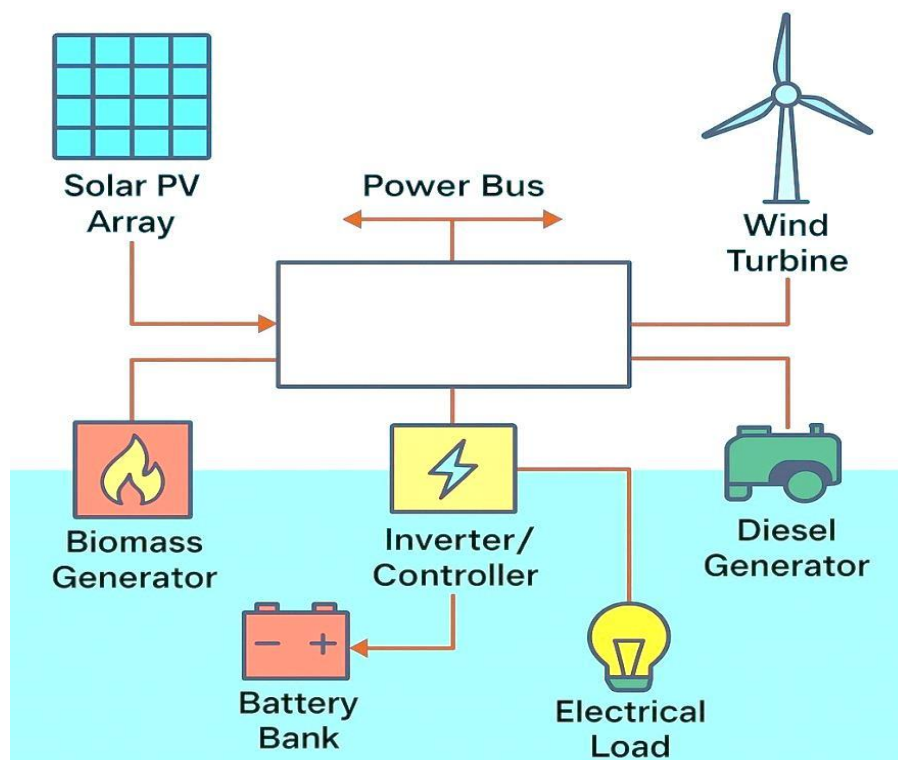


Figure 2. Schematic Description of a HRES

4. Research Approach and Methods of Analysis

A representative rural location is selected, and its energy demand profile is estimated based on household and community-level electricity usage [15].HOMER software is then used to simulate thousands of system configurations, calculating performance indicators .

4.1 HOMER Modelling Steps

The modelling process using HOMER software involves a series of structured steps to simulate and optimize hybrid renewable energy systems. The process begins by defining the project settings, including the simulation time frame, project lifetime, discount rate, inflation, and fuel price assumptions. Next, the electrical load profile for the target rural area is entered, typically based on hourly or daily energy consumption patterns reflecting residential and community usage [16]. Biomass availability is then imported, either from local databases or HOMER's built-in datasets. Defined with their technical specifications and associated costs. HOMER then creates a range of hybrid system configurations by combining these components, and simulates their performance over the selected time horizon. A sensitivity analysis is also performed by varying critical parameters. Finally, HOMER provides detailed outputs that summarize the optimal configuration based on both economic and environmental criteria [17].

4.2 Economic and environmental parameters

The assessment of HRES requires careful evaluation of both economic and environmental parameters. Economically, the key parameters include direct comparison between different configurations. Capital cost, operational cost, salvage value, and payback period are also considered in the economic evaluation. Environmentally, the system's impact is analyzed through parameters such as CO₂, NO_x, SO_x, and PM generated, particularly from diesel generator usage [18]. The renewable energy fraction is another critical indicator, showing the percentage of total energy supplied by renewable sources, thus reflecting the system's contribution to reducing dependency on fossil fuels. These parameters help in identifying the optimal system configuration that not only minimizes costs but also maximizes environmental benefits, aligning with the goals of sustainable rural electrification.

5. RESULTS AND DISCUSSION

5.1 System Design and Simulation

The system process involves selecting appropriate components and configurations to ensure the HRES can location efficiently and sustainably. Based on the estimated load profile and biomass feedstock, suitable energy generation technologies are chosen. Each component is defined in the HOMER software with its technical specifications such as rated capacity, efficiency, lifespan and economic parameters, including capital, replacement, and O&M costs [19]. HOMER then simulates various configurations by combining these components under different operating strategies. The simulation considers hourly load variations, seasonal resource fluctuations, and dispatch strategies over the project lifespan. The output provides detailed performance indicators including total power generation [20]. The simulation also evaluates the economic and environmental impacts, enabling comparison between configurations and emissions.

5.2 Input parameters for simulation

It requires a comprehensive set of input parameters. The first set of inputs includes the load profile, which specifies the hourly or daily throughout the year. The next group of inputs involves the technical specifications of each system component, including rated capacity, efficiency, operational limits. HOMER also requires financial parameters such as the project lifetime, discount rate, and inflation rate to compute lifecycle costs. Lastly, environmental data such as fuel emission factors (e.g., CO₂, NO_x, SO_x per liter of diesel) are inputted to assess the ecological impact of each configuration. These input parameters form the foundation for accurate simulation and optimization of the HRES in HOMER. In this study, various hybrid system configurations were tested using HOMER software to determine the most technically and economically feasible option for rural electrification. The configurations were developed by combining different energy sources. The first configuration considered was a PV-Diesel-Battery system, a commonly used setup in remote areas. The second configuration tested was a PV-Wind-Battery system. A third setup integrated PV-Biomass-Battery, utilizing locally available organic waste as a dispatchable energy source. Another configuration combined Wind-Diesel-Battery, focusing on locations with strong wind potential. A more complex system combining PV-Wind-Biomass-Diesel-Battery was also tested to analyze the performance of a fully hybridized system.

Table: 1 Different Configurations Tested in HOMER Simulation

Configuration ID	System Components	Description
Config-1	PV + Diesel + Battery	Common off-grid system; diesel as backup to solar
Config-2	PV + Wind + Battery	Fully renewable system; solar and wind complement each other
Config-3	PV + Biomass + Battery	Combines intermittent solar with dispatchable biomass generator
Config-4	Wind + Diesel + Battery	Wind-reliant system with diesel support
Config-5	PV + Wind + Biomass + Diesel + Battery	Fully hybridized system; designed for high reliability and minimum fuel usage

This system leverages the abundant solar energy during the day and dispatchable biomass during non-solar hours, with diesel acting as a backup only when necessary. In comparison, the PV–Diesel–Battery system, though simpler and widely used, exhibited a higher dependency on fossil fuel, resulting in increased fuel consumption, operating cost, and carbon emissions. The PV–Wind–Battery configuration, while environmentally superior due to zero emissions, was economically less favorable in regions with inconsistent wind resources and required higher capital investment for wind turbines. The fully hybridized system reliability and lowest unmet load but involved complex integration and the highest capital cost, making it more suitable for larger-scale microgrids rather than small rural villages.

Environmental performance was also assessed in terms of carbon dioxide (CO₂) emissions and diesel fuel usage. Systems with higher renewable fractions significantly reduced greenhouse gas emissions. The PV–Biomass system, in particular, achieved a notable reduction in emissions while using locally sourced biomass, promoting sustainability and energy independence. For example, a 20% increase in diesel fuel price increased the NPC of diesel-reliant systems considerably, whereas solar–biomass-based systems remained relatively stable. These findings suggest that integrating solar PV and biomass generation with moderate battery storage offers an effective pathway for delivering clean, reliable, and affordable electricity to rural off-grid communities.

5.3 Renewable fraction and emissions reduction

The renewable fraction and emissions reduction are critical performance indicators for evaluating the sustainability of HRES. A higher renewable fraction indicates greater reliance on clean energy and reduced dependency on fossil fuels. In HOMER configurations often achieve renewable fractions ranging from 70% to over 90%, depending on resource availability and system design. This significant renewable integration directly contributes to a reduction in harmful emissions. Compared to a diesel-only setup, a hybrid system with a high renewable fraction can reduce CO₂ emissions by 60% to 80% or more. Such reductions not only improve the environmental profile of rural electrification projects (Figure 3).

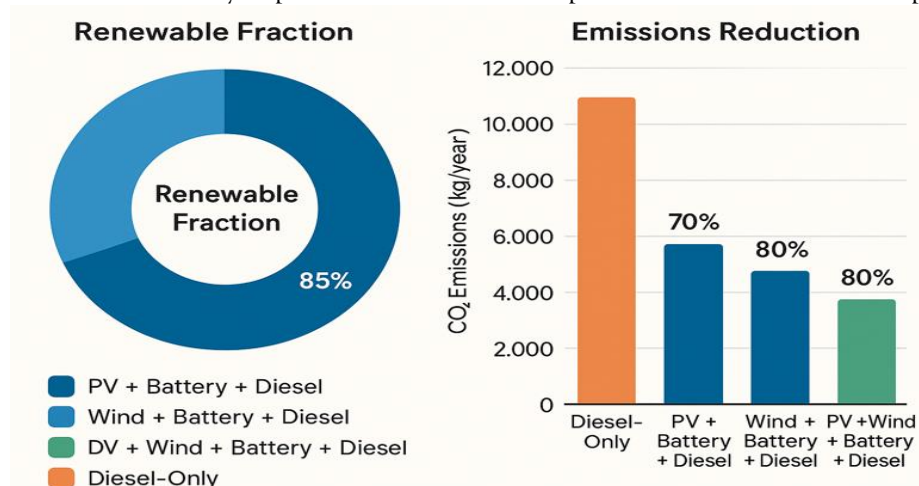


Figure 3. Renewable fraction and emissions reduction

5.4 Impact of system components on performance

Solar PV modules are crucial for daytime power generation, and their efficiency depends on factors such as irradiance, orientation, and temperature. Wind turbines contribute by generating electricity during windy conditions, especially complementing solar energy during non-daylight hours or cloudy periods. Diesel generators serve as a backup source, ensuring reliability but increasing operational costs and emissions if overused. Finally, the energy management system or controller coordinates all components to maximize renewable energy use while minimizing costs and emissions. An integrated and optimized approach to component selection and control strategy is essential for achieving high efficiency, reliability, and environmental sustainability in off-grid electrification research (Figure 4).

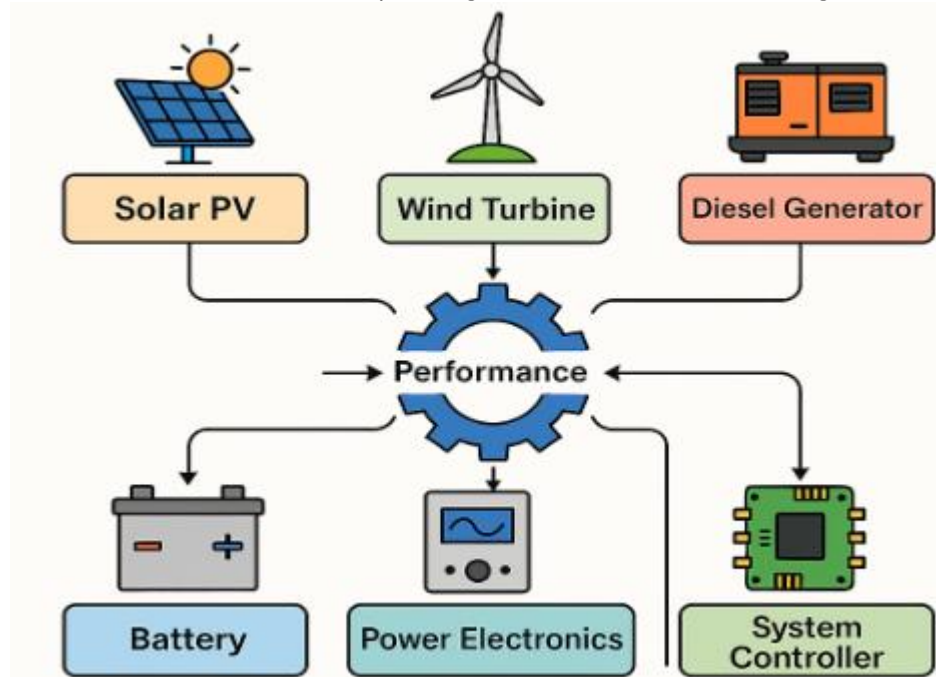


Figure 4. Impact of system components on performance

CONCLUSION.

It is particularly useful for modelling HRES for off-grid rural electrification, where reliable grid access is either unavailable or economically infeasible. It ensures a steady, cost-efficient, and environmentally friendly power supply. HOMER evaluates thousands of possible system configurations using input data, resource availability, component technical parameters, and cost information. The impact of individual components on performance is substantial. Solar and wind resources contribute clean energy, while batteries store excess energy and ensure reliability. Diesel generators serve as backups during low renewable periods but increase fuel consumption and emissions. Smart controllers and inverters optimize power flow and system operation. HOMER also enables sensitivity analysis to account for fuel price changes, load growth, or variability in renewable resources, making the system robust and adaptable to future uncertainties. In conclusion, HOMER-based design and simulation of HRES provide a techno-economically optimized pathway for sustainable rural electrification. These systems not only bridge the energy access gap but also support environmental conservation and socioeconomic development in remote and underserved regions.

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