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Optimized use of local renewable resources in decentralized hybrid mode for sustainable energy solution of rural India

Dr.Parag R. Wadnerkar
Principal,Rajarshree Shahu Science College,
Chandur Rly District Amravati
principal@rssc.edu.in

Abstract: The growing energy demand in rural India, coupled with challenges related to grid connectivity, necessitates the development of decentralized hybrid renewable energy solutions. This study explores the **optimized utilization of local renewable resources** such as solar, wind, biomass, and small hydro in a decentralized hybrid energy model. By integrating multiple renewable sources with advanced energy management systems, the proposed approach enhances reliability, efficiency, and sustainability. **Optimization techniques**, including **artificial intelligence (AI)-based predictive models and IoT-enabled smart grids**, are employed to balance supply and demand dynamically. The study highlights **techno-economic feasibility, environmental benefits, and policy recommendations** for effective implementation. Results demonstrate that a well-optimized hybrid model can significantly reduce reliance on fossil fuels, lower costs, and provide uninterrupted power to rural communities. This work contributes to India's sustainable development goals by fostering **energy security, economic growth, and environmental conservation**.

Keywords: Decentralized energy system, Hybrid renewable energy, Optimization techniques, Rural electrification, Solar-wind-biomass integration, IoT-enabled smart grid, AI-based energy management, Sustainable energy solutions, Techno-economic feasibility, Energy security

Introduction

The ever-increasing global population, high living standards, growing industrialisation, and urbanisation are all factors that are contributing to the rise in the need for energy on a worldwide scale. According to studies from the World Bank and the International Energy Agency (IEA), the worldwide installed power capacity of emerging nations may treble over the next forty years in order to satisfy the ever-increasing demand for energy. At this point in time, the energy utility services are mostly controlled by energy systems that are based on fossil fuels, which account for around sixty percent of the overall energy share. The conventional resources, on the other hand, have a limited amount, are rapidly diminishing, and release greenhouse gases (GHGs), which are the primary contributors to the phenomenon of global warming. In order to mitigate the effects of climate change, nations that are members of the United Nations (UN) have signed a deal to limit the increase in global temperature to 1.5 degrees Celsius over the level that existed before the industrial revolution. The Conferences of Parties (COPs) are the means by which the International Panel on Climate Change (IPCC) provides support for this organisation. Having access to energy that is dependable brings to an improvement in productivity and contributes to the economic growth of society. One of the Sustainable Development Goals (SDGs), also known

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as SDG 7, was suggested by the United Nations in order to improve the global human development index (HDI). The goal of this particular SDG is to provide everyone with low-cost, environmentally friendly, and dependable power. Over 1.3 billion people living in distant communities are unable to access the stable grid energy owing to technological and economic restrictions, as stated in the second study published by the International Energy Agency (IEA). Since this is the case, governments have lately placed a greater focus on boosting the proportion of their energy supply that comes from locally accessible renewable energy resources. Not only does the creation of renewable energy minimize carbon emissions, but it also enhances energy access services, which in turn promotes sustainable development in places that are geographically isolated. In the event that the proportion of renewable energy is increased to 45% by the year 2030, it is anticipated that the emissions from the energy sector would be reduced by as much as 11%. There are a number of limitations associated with these renewable energy resources, including dilution in energy density, intermittency, unequal distribution, and the need for large capital expenditure. Despite the fact that these resources are potential possibilities for the future, they also have this drawback. "Hybridization," which refers to the integration of various renewable energy resources that are supported by appropriate storage modules and/or other backup systems (such as diesel generator (DG) sets), is one of the conceivable methods that may be used to overcome these restrictions. It is possible that the expansion of the national grid to these rather distant communities would not be cost-effective for the purpose of electrifying these settlements. One of the potential solutions to this problem is the implementation of a decentralized hybrid energy system, often known as a HES. One of the most significant users and providers of energy is India, which is a big developing nation with a population of 1.4 billion people and an installed capacity of 425 gigawatts at the moment. India's energy consumption is continually growing as a result of the country's high population density and rising industrialization. The majority of India's energy needs are still met by fossil fuels, which are the most abundant source of energy. India, which is one of the economies that is developing at the quickest rate, is confronted with a twofold challenge: satisfying its increasing energy demand while also ensuring that it is sustainable. Rural areas of India, which are home to roughly 65 percent of the country's population, continue to face challenges such as inconsistent grid access, frequent power outages, and reliance on fossil fuels as a source of energy. There is a considerable number of rural settlements that are either not electrified at all or have inadequate access to electricity, which results in economic stagnation and worse living circumstances. Traditional centralised power production and distribution are subject to a number of restrictions, including significant transmission losses, limits in infrastructure, and cost restraints.

To address these challenges, decentralized **hybrid renewable energy systems (HRES)** emerge as a viable alternative. They leverage locally available renewable resources like **solar, wind, biomass, and small hydro** to generate and distribute energy in an optimized manner. Such systems not only improve energy access but also reduce environmental impact and dependence on conventional energy sources.

1.2 Need for Decentralized Hybrid Renewable Energy Solutions

The current energy scenario in rural India is characterized by:

- **Grid instability** due to inadequate infrastructure.
- **High dependency on fossil fuels**, leading to increased **carbon emissions and energy costs**.
- **Unreliable power supply**, hindering economic activities and essential services like healthcare and education.
- **Geographical constraints**, making grid expansion expensive and challenging in remote areas.

A **decentralized hybrid renewable energy system (DHRES)** integrates multiple energy sources at a localized level, ensuring **energy security, cost-effectiveness, and sustainability**. By combining solar photovoltaics (PV), wind turbines, biomass gasifiers, and micro-hydro plants, an optimal energy mix can be developed to **match local resource availability with demand patterns**.

1.3 Advantages of Hybrid Renewable Energy Systems

Compared to standalone energy solutions, **hybrid renewable energy systems (HRES)** provide:

- **Reliability and stability**: Integrating multiple energy sources reduces dependency on any single resource.
- **Scalability and flexibility**: Modular design allows for expansion based on energy demand.
- **Cost-effectiveness**: Reduction in transmission losses and operational costs.
- **Sustainability**: Minimal environmental footprint due to renewable energy integration.

1.4 Role of Emerging Technologies in Optimizing Hybrid Energy Systems

Advancements in **artificial intelligence (AI), machine learning (ML), and the Internet of Things (IoT)** are transforming energy management systems. These technologies enable:

- **Real-time monitoring and predictive analytics** for optimized energy distribution.
- **Smart grids** for demand-side management and load balancing.
- **Automated control systems** to enhance operational efficiency.

Such **intelligent energy management frameworks** are critical for ensuring the success of decentralized renewable energy solutions in rural India.

1.5 Government Policies and Initiatives Supporting Renewable Energy in India

The Indian government has launched several programs to promote **renewable energy adoption**, including:

- **National Solar Mission**: Aims for **280 GW solar capacity** by 2030.
- **Deen Dayal Upadhyaya Gram Jyoti Yojana (DDUGJY)**: Focuses on **rural electrification and decentralized energy models**.
- **Renewable Energy Development Fund**: Provides financial support for hybrid and off-grid projects.Despite these initiatives, challenges related to **policy implementation, financial constraints, and technical integration** persist, requiring further research and strategic planning.

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For comprehensive action planning, the study's overarching goal is to determine which energy solutions, arising from competing concerns, should take precedence. The suggested approach took linguistic uncertainty into account while calculating ranks and weights. So, to assess the energy strategy's priorities in order to follow the sustainable development route, the suggested technique is more efficient. The suggested technique combines the SWOT analysis with MCDM to create an effective action plan, which is called the HFL-MCDM. To estimate the weights and rankings of the strategies, the HFL-MCDM technique is used, taking into account the complicated, ambiguous, and unpredictable nature of energy strategy prioritisation. We assess the weights of the generated methods using HFL-Analytic Hierarchy Process (AHP). The HPL-Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) technique is next evaluated for estimating the rank of these methods. The solution's robustness is further assessed by doing the sensitivity analysis.

India's energy planning situation:

New energy policies and strategies are necessary on a worldwide scale, and India is no exception (Government of India, 2016). The energy demand-supply gap in India is widening due to the aforementioned issue, even though the government of India declared "Indian vision 2040" to provide "Power to all" in the nation in a way that is dependable, sustainable, efficient, and affordable (NITI Aayog, 2017). (NITI Aayog, 2022b). The country's future energy security is jeopardised, and economic progress is impeded as a result. In order to accomplish the SDGs and ensure the country's energy security in the future, the development of new energy policies must be prioritised (NITI Aayog, 2017). Figure 1 displays the methods of this investigation in detail.

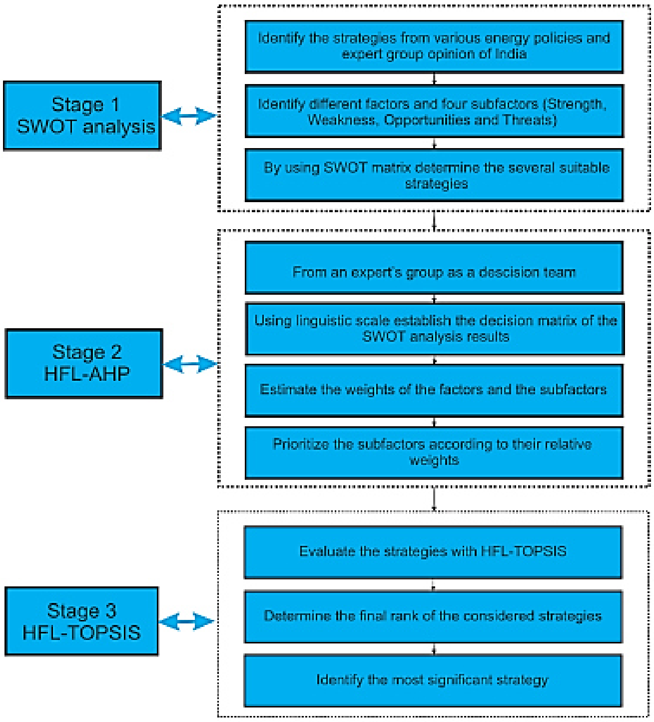

Fig. 1: Flowchart of the integrated methodology

According to Fig. 1, different tools with the inputs from the previous phase are integrated in this study to decide the priorities of the decided strategies for a better sustainable energy transition

In most cases, a hybrid renewable energy system (HRES), also known as hybrid power, is comprised of two or more renewable energy sources that are used in conjunction with one another to achieve higher system efficiency as well as better equilibrium in the supply of energy [1]. As a result of the rapid depletion of fossil fuels, there is an urgent need for alternate sources of energy in order to meet the ever-increasing demand for energy. Increasing evidence of the phenomenon of global warming is yet another significant cause for us to cut down on our usage of fossil fuels. Technologies for the production of power that are less harmful to the environment will contribute significantly to the future supply of electricity. Technologies that generate electricity from renewable energy sources include wind, photovoltaic (PV), micro hydro (MH), biomass, ocean wave, geothermal, and tides. These technologies are included in the category of renewable energy technologies. The nature of renewable energy resources, on the other hand, indicates that they are very site-specific and intermittent. Therefore, as demand increases in stand-alone mode, single technology-based systems are associated with high system cost and low reliability. As a result, the concept of hybrid renewable energy system has been introduced for power generation in stand-alone applications in order to deal with similar limitations that are associated with single technology-based systems. The weather conditions have a significant impact on the amount of electricity that can be generated by wind and solar energy plants. In light of this, there is no one energy source that is capable of delivering electricity that is both dependable and cost-effective [4]. In the event that renewable energy sources are combined, there is a possibility that variations in power distribution may occur. It is possible to make use of energy storage technologies, such as storage batteries (SBs), in order to reduce or even eliminate the fluctuations. There is a site-specific need for the appropriate size of the storage system, which is determined by the quantity of renewable energy and the demand [5, 6]. When the right mix of solar and wind power is used at a particular location, the amount of storage capacity that is now required might be cut down to an absolute minimum.Wind Turbine

The wind turbines convert the mechanical energy that is produced by the wind to electrical energy. To use this electrical energy a voltage and a frequency regulation has been needed. Wind turbines operate on a simple principle. The energy in the wind turns two or three propeller-like blades around a rotor. The rotor is connected to the main shaft, which spins a generator to create electricity.

Essentials Of Hybrid System Optimizations

An assessment must be carried out on the basis of power reliability and system life-cycle cost in order to identify the optimal combination for a hybrid system in order to accomplish the task of meeting the load demand.

The power Consistency of the system When calculating the dependability of the hybrid system, there are a few different approaches that may be used. There are many different types of losses, including Loss of Load Probability (LOLP), System Performance Level (SPL), Loss of Load Hours (LOLH), and Loss of Power Supply Probability (LPSP) [10, 11]. A low-power supply probability (LPSP) is the likelihood that an inadequate power supply will occur as a consequence of the hybrid system's inability to meet the load demand. To put it another way, the LOLP is a measurement of the chance that the demand of the system will surpass the capacity of the system's power supply in a certain amount of time. According to the definition provided by [12], the SPL is the chance that the load cannot be supplied. A technique for the evaluation on the basis of the loss of load risk (LOLR) was proposed by AlAshwal and Moghram [13] in order to determine a percentage for solar and wind energy in a hybrid system.

The cost of the system There are a number of economic parameters that are used in the process of analysing the cost of the system. These include the Net present cost, the Levelized Cost of Energy [9], and the life-cycle cost [10]. It is common practice to assume the life of the PV modules to be the same as the life of the system [11]. This ratio is known as the levelized cost of energy, and it is calculated by dividing the total annualised cost of the system by the annual amount of power that is provided by the system..

HRES OPTIMIZATION TECHNIQUES

It is possible to establish the optimal size of a battery bank, photovoltaic array, wind turbine, hydro generating capacity, and other generation system for an autonomous or grid integrated hybrid renewable energy system (HRES) for a particular load by using a simulation software that has been carefully constructed. Researchers used a wide range of optimisation strategies, including graphical construction, probabilistic method, iterative technique, artificial intelligence (AI), dynamic programming, linear programming, and multi-objective, in order to optimise hybrid photovoltaic (PV) and wind energy systems.

Visual Construction of Graphics An approach known as Graphical Construction has been proposed by Borowy and Salameh [15], which is based on the utilisation of long-term data of solar radiation and wind speed that has been collected for each hour of the day over a period of thirty years. An additional sort of graphical approach has been provided by Markvart [16] in order to best construct a hybrid solar–wind power generating system by taking into consideration the monthly-average values of solar and wind energy. Strategies Based on Probability It is important to take into consideration the influence of solar radiation and wind speed fluctuation in the design of the system when using a probabilistic approach to pricing. In his paper [17], Bucciarelli suggested a technique for scaling that treats the fluctuation in storage energy as a random walk. An approximate representation of the probability density for the daily increase or decrement of storage level was obtained via the use of a two-event probability distribution [18].

The Technique of Iteration One of the strategies that are included in the HRES optimisation techniques is called the Iterative Technique. A Hybrid Solar–wind System Optimisation (HSWSO) model was suggested by Yang et al. [19]. This model makes use of the iterative optimisation approach, which is based on the LPSP model and the Levelized Cost of Energy model, respectively, for power reliability and system cost. Additionally, Kellogg et al. [20] proposed an iterative optimisation approach to pick the wind turbine size and PV module number using an iterative process to make the difference between the produced and required power (DP) as near to zero as feasible over a period of time. This was done in order to maximise the amount of power that was created and the amount of power that was demanded.

In the field of computer science, artificial intelligence is a subfield that focusses on the development of intelligent computers that can perform and communicate in the same manner as people. Speech recognition, learning, planning, and problem solving are just some of the functions that computers equipped with artificial intelligence are meant to do. Methods of artificial intelligence, such as Artificial Neural Networks, Genetic Algorithm, Fuzzy Logic, PSO (Particle Swarm Optimisation), and ACO (Ant Colony Optimisation), are often used in the process of optimising hybrid systems in order to maximise the economic advantages that they provide. For the purpose of optimising solar systems, Kalogirou [21] created an optimisation model that makes use of artificial neural networks and genetic algorithms. These are the most effective ways since they assist in finding the global answer to issues that are difficult to solve or understand.

The approach relies on software Among the commercial software that is widely used for the purpose of developing and analysing hybrid power systems is HOMER, which is developed by the National Renewable Energy Laboratory (NREL) in the United States [22]. The HOMER program takes into account the solar insolation, the electrical demand, the hybrid generator technical specifications, the costs, the limitations, the controls, and the kind of dispatch strategy as its input. 5. PERSPECTIVES ON THE FUTURE There has been a significant amount of progress made in terms of research and development for renewable energy systems. However, there are still certain challenges to overcome in terms of their effectiveness and getting the most out of their utilisation. Listed below are the difficulties that the designer must contend with. Renewable energy sources, such as solar photovoltaics and fuel cells, need cutting-edge technology in order to extract a greater quantity of electricity that may be put to productive use. Solar energy's low efficiency presents a significant barrier to full utilisation of its potential. There is a significant need for a decrease in the production costs of these renewable energy sources. It need to be verified that there ought to be a significant quantity of power loss in the electronic gadgets that are powered by electricity. The life-cycle of the storage technologies has to be extended by the use of novel technical solutions.

One of the most important aspects that contributes to the economic development of rural regions in any nation is the availability of energy. The fact that the bulk of India's population lives in rural regions that are not connected to an electric utility grid is the primary factor that is preventing the country's overall growth. Rural electrification is an essential component in the development of rural regions, as it contributes to the attainment of economic growth and the enhancement of the standards of living in rural communities. According to the Census of 2011, more than 77 million homes in India continue to utilise paraffin as a source of illumination. The electricity supply in the electrified villages is of poor quality, there is a limited quantity of it, and it is inconsistent. The circumstances that persisted compelled us to look into additional possibilities in order to satisfy the day-to-day requirements of the energy demand. The government of India has initiated a number of programs, including the Rajiv Gandhi Grameen Vidyutikaran Yojana (RGGVY) and the Remote Village Electrification Programme (RVEP), amongst others [1]. Along with the aforementioned programs, the government of India proposed the establishment of the Jawaharlal Nehru National Solar Mission as part of the National Action Plan on Climate Change. The mission would have the objective of producing 20,000 megawatts of solar electricity by the year 2022, 1,000,000 megawatts by the year 2030, and 2,000,000 megawatts by the year 2050 [2]. In spite of the efforts and initiatives taken by the government of India, the energy that is derived from fossil fuels, such as coal and petroleum, is still regarded to be the major source of energy. As of the 30th of June in the year 2016-2017, the total installed capacity was 304.50 GW. The generating mix consisted of a combination of thermal, which included coal gas and diesel, accounting for 70% of the total, hydro (14%), renewable (14%), and nuclear (2%). It is [3]. The resources that are based on fossil fuels, such as coal, natural gas, and oil, are the primary contributors to the generation of electricity in India. There is a correlation between the use of these conventional energy supplies and the rise in the amount of carbon emissions produced. However, the government of India is showing a great deal of seriousness in its efforts to decrease the amount of carbon emissions and the percentage of electrical energy that is produced from fossil fuels, while simultaneously increasing the amount of electrical energy that is produced from renewable energy sources. Increasing the number of activities that create power from renewable energy sources is something that the Ministry of New and Renewable Energy of the Government of India encourages individuals to do.

The development of technology for renewable energy has led to a drop in the cost of the energy as well as an increase in the scope of environmentally friendly environmental practices, which has resulted in it being more accessible to supply the load during the intermittent period. The hybrid energy system is an outstanding option for providing a continuous and reliable supply of load in distant rural locations where the expansion of the grid is either difficult and costly or if the supply from the grid is unavailable the majority of the time. The standard diesel generator may be used as a backup generator in a hybrid energy system [4, 5, 6]. Hybrid energy systems are comprised of a mix of one or more renewable energy sources, such as solar photovoltaic, wind energy, micro-hydro, and other similar sources. It is suggested to use a hybrid energy system after conducting a comprehensive study of the site, which takes into account the availability of the kind of source, the amount of that source, and the load profile of the site area. Solar energy is the most readily accessible form of energy for the location that is being conducted research on. This article proposes a concept for a hybrid energy system that is grid-based and powered by SPV diesel for the location that is being investigated.

In order to construct a hybrid energy system, there are several approaches that may be taken to combine various renewable energy and alternative energy sources. These techniques may be categorised as dc-coupled, ac-coupled, or hybrid-coupled, depending on their specific use. AC linked is the system architecture that is used in the hybrid energy system. This design allows for the many alternative energy and renewable energy sources to be connected to the AC Bus. In addition, primary loads are linked to the AC Bus by means of power electronic interface circuits

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(if they are required), as seen in figure 1. At the same time, the AC bus is linked to the utility grid. Providing electricity to the load as well as providing power to the energy storage system is the responsibility of the utility grid. In the event that there is no power from the grid, the energy storage system supplies the AC Bus with energy via the use of power electronic converters. [8].

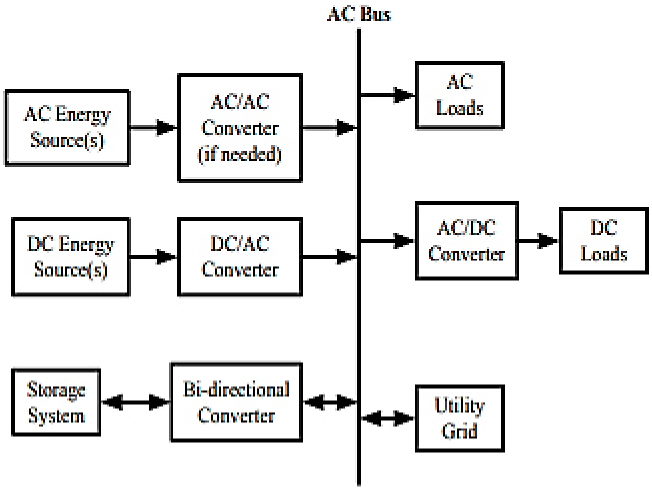

Fig. 2: Schematic of ac-coupled hybrid energy system

In this paper, Hybrid Optimization Model for Electric Renewable (HOMER version 3.10.3) has been used as simulation tool for sizing and optimization of hybrid energy system. It has a number of energy component models and calculates appropriate technology alternatives based on cost and availability of resources. Analysis with HOMER needs resource data, economic constraints and control methods etc.

Conclusion

A sustainable and dependable energy solution for rural India may be achieved via the optimised utilisation of local renewable resources in a decentralised hybrid mode. Energy independence, efficiency, and sustainability may be attained by rural regions via the integration of several renewable energy sources, including solar, wind, biomass, and small hydro. In underserved and far-flung areas where expanding the grid would be difficult and expensive, decentralised hybrid renewable energy systems (DHRES) provide an attractive substitute for traditional grid-based electrification.These systems are even more efficient and reliable when cutting-edge technologies like smart grids, blockchain, the internet of things (IoT), artificial intelligence (AI), and machine learning (ML) are integrated. Smart grids supported by the Internet of Things allow for load balancing and remote monitoring, while AI-based predictive analytics guarantee optimised energy distribution via real-time energy management. Hydrogen fuel cells and lithium-ion batteries are two examples of energy storage technologies that may reduce the unreliability of renewable power.Decentralised hybrid renewable energy systems have several benefits, but they aren't yet widely used because to things like high starting investment prices, gaps in policy implementation, and a lack of technical knowledge. These obstacles, however, may be surmounted with the help of the government's robust backing, smart investments, and creative funding structures. Rural electricity might be revolutionised via decentralised renewable energy initiatives like the National Solar Mission, DDUGJY, and microgrid projects. The optimisation of hybrid renewable energy systems offers a long-term solution to the rural energy issue in India. If these plans are put into action, they will help achieve global climate targets, speed up India's transition to renewable energy, and improve socioeconomic growth. Unlocking the full potential of indigenous renewable resources and guaranteeing energy security for rural India requires a technology-driven, community-focused, and policy-backed strategy.

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