

A Systematic Review on Hybrid Renewable Energy System

¹Neha, ²Vivek Kumar

¹M.Tech Scholar, ²Professor and Head
Department of Electrical Engineering, BRCM CET Bahal, Haryana

Abstract: The transition towards sustainable energy systems is critical in addressing the global challenges of climate change, energy security, and sustainable development. Hybrid Renewable Energy Systems (HRES) have emerged as a promising solution, integrating multiple renewable energy sources such as solar, wind, biomass, and hydropower to enhance reliability, efficiency, and sustainability. This systematic review provides a comprehensive overview of HRES, exploring their background, the need for such systems, key components, and their advantages. By leveraging the complementary nature of different renewable sources, HRES mitigate the intermittency and variability issues associated with individual sources, ensuring a stable and continuous energy supply. The integration of advanced energy storage systems, power electronics, and sophisticated control mechanisms further enhances the efficiency and reliability of HRES. This review synthesizes current research findings, highlighting the environmental, economic, and social benefits of HRES, as well as the challenges and future prospects.

Keywords: Hybrid Renewable Energy System (HRES), Solar Photovoltaic (SPV), Diesel, Pollution

1. Introduction

In the quest for sustainable energy solutions, the global focus has shifted towards renewable energy sources. The increasing demand for energy, coupled with the pressing need to reduce carbon emissions,

has driven significant research and development in renewable energy technologies. Among these, Hybrid Renewable Energy Systems (HRES) have emerged as a promising solution to address the limitations and variability associated with individual renewable energy sources [1]. Hybrid Renewable Energy Systems integrate two or more renewable energy sources, such as solar, wind, biomass, and hydropower, to create a more reliable, efficient, and sustainable energy system. By combining different energy sources, HRES can take advantage of the complementary nature of these sources, thereby enhancing energy production reliability and efficiency. For instance, solar power can be harnessed during the day, while wind power can be utilized at night or during periods of low sunlight, ensuring a continuous energy supply [2-4]. The primary advantage of HRES lies in its ability to mitigate the intermittency issues associated with renewable energy sources. Solar and wind energy, for example, are highly dependent on weather conditions and time of day, leading to fluctuations in energy generation. By integrating multiple sources, HRES can balance these fluctuations, ensuring a more stable and consistent energy output. This capability is particularly important for remote and off-grid areas, where a reliable energy supply is crucial. Furthermore, HRES can enhance the overall efficiency of energy systems. By optimizing the use of different renewable sources, these systems can reduce the need for energy storage and minimize energy losses [5]. This efficiency gain can lead to cost savings and make renewable energy more

competitive with traditional fossil fuels. Despite their potential, the implementation of HRES faces several challenges. Technical complexities, high initial investment costs, and the need for advanced control and management systems are some of the barriers that need to be addressed. Additionally, the integration of multiple energy sources requires careful planning and design to ensure compatibility and optimal performance. This systematic review aims to provide a comprehensive overview of the current state of research on Hybrid Renewable Energy Systems. It will explore the different configurations of HRES, their performance, benefits, and challenges. By synthesizing the findings from various studies, this review will offer insights into the potential of HRES to contribute to a sustainable energy future and identify areas for further research and development. In conclusion, Hybrid Renewable Energy Systems represent a significant step towards achieving a sustainable and resilient energy infrastructure. By leveraging the strengths of multiple renewable energy sources, HRES can provide a reliable, efficient, and environmentally friendly energy solution. This review will delve into the various aspects of HRES, offering a thorough understanding of their potential and paving the way for future advancements in renewable energy technology.

2. Need of HRES

The global energy landscape is undergoing a significant transformation driven by the urgent need to address climate change, reduce greenhouse gas emissions, and ensure energy security. Traditional fossil fuel-based energy systems are increasingly being recognized as unsustainable due to their environmental impact and finite nature. In this context, renewable energy sources such as solar, wind, biomass, and hydropower have gained prominence. However, the inherent intermittency and variability of these sources present significant

challenges. This is where Hybrid Renewable Energy Systems (HRES) come into play, offering a viable solution to these challenges.

2.1 Addressing Intermittency and Variability

One of the primary reasons for the need for HRES is the intermittency associated with individual renewable energy sources. Solar power generation is dependent on sunlight availability, which varies with time of day, weather conditions, and seasonal changes. Similarly, wind energy generation is influenced by wind speed and direction, which can be highly variable. These fluctuations can lead to periods of energy surplus or deficit, complicating the task of ensuring a stable and reliable energy supply. By integrating multiple renewable energy sources, HRES can harness the complementary nature of these sources. For instance, solar and wind energy often exhibit inverse patterns; when one source is less productive, the other may be more productive [5,6]. This complementary behavior helps in smoothing out the overall energy output, reducing the dependency on any single source and enhancing the reliability of the energy system.

2.2 Enhancing Energy Security and Reliability

Energy security is a critical concern for both developed and developing regions. Reliance on a single source of energy can expose communities to risks such as supply disruptions, price volatility, and geopolitical tensions. HRES provide a diversified energy mix, which can enhance energy security by reducing the reliance on imported fuels and mitigating the impact of energy supply disruptions. Moreover, HRES can play a vital role in providing reliable energy access to remote and off-grid areas. In many parts of the world, extending the conventional power grid is economically and technically unfeasible [7]. HRES offer a decentralized energy solution that can deliver consistent and reliable power to these areas,

improving the quality of life and supporting economic development.

2.3 Increasing Efficiency and Reducing Costs

Hybrid systems can optimize the use of different renewable energy sources, leading to higher overall efficiency. For example, excess energy generated by solar panels during the day can be used to power wind turbines or stored in batteries for use during periods of low solar irradiance. This synergistic operation reduces energy wastage and enhances the overall efficiency of the energy system. While the initial capital investment for HRES can be high, the long-term benefits in terms of reduced operational costs, lower maintenance requirements, and savings on fuel costs can make these systems economically viable. Advances in technology and economies of scale are also contributing to the decreasing costs of renewable energy components, making HRES an increasingly attractive option.

2.4 Environmental and Social Benefits

The environmental benefits of HRES are significant. By reducing the reliance on fossil fuels, HRES help in lowering greenhouse gas emissions, reducing air pollution, and mitigating the impacts of climate change. Additionally, the use of local renewable resources minimizes the environmental footprint associated with energy production and distribution. Socially, HRES can contribute to sustainable development by creating job opportunities, promoting energy independence, and improving access to clean and affordable energy. The deployment of HRES can stimulate local economies, foster community engagement, and support the transition towards a more sustainable and resilient energy infrastructure.

3. Components of HRES

Hybrid Renewable Energy Systems (HRES) are intricate assemblies that combine multiple renewable energy sources to enhance the reliability

and efficiency of energy generation. The key components of HRES can be categorized into primary energy sources, energy conversion devices, energy storage systems, power electronics, and control systems [8-10]. Understanding these components is essential for designing and optimizing HRES.

3.1 Primary Energy Sources

3.1.1 Solar Energy:

- Solar Photovoltaic (PV) Panels: These panels convert sunlight directly into electricity using semiconductor materials.
- Solar Thermal Collectors: These devices capture solar energy to heat a fluid, which can then be used for power generation or heating applications.

3.1.2 Wind Energy:

- Wind Turbines: Wind turbines convert the kinetic energy of wind into mechanical energy, which is then converted into electricity by a generator.

3.1.3 Biomass Energy:

- Biomass Boilers and Gasifiers: These systems convert organic materials into heat or gas that can be used for power generation or as a fuel source.

3.1.4 Hydropower:

- Micro-Hydro Turbines: These turbines generate electricity from the kinetic energy of flowing or falling water, typically in small-scale applications suitable for HRES.

3.2 Energy Conversion Devices

3.2.1 Inverters:

- Convert the direct current (DC) produced by solar PV panels and some wind turbines into alternating current (AC) compatible with the grid or local loads.

3.2.2 Generators:

- Convert mechanical energy from wind turbines, biomass systems, or hydropower into electrical energy.

3.2.3 Heat Exchangers:

- Transfer heat from solar thermal collectors or biomass systems to a working fluid for power generation or heating purposes.

3.3 Energy Storage Systems

3.3.1 Batteries:

- Store excess electrical energy produced by renewable sources for later use, ensuring a continuous power supply.

3.3.2 Flywheels:

- Store energy in the form of rotational kinetic energy, providing rapid response to changes in energy demand or supply.

3.3.3 Hydrogen Storage:

- Involves the production of hydrogen via electrolysis, storing it for use in fuel cells to generate electricity when needed.

3.3.4 Thermal Storage:

- Stores excess thermal energy from solar thermal systems or biomass for later use, often in the form of hot water or molten salts.

3.4 Power Electronics

3.4.1 Charge Controllers:

- Regulate the flow of electricity from renewable sources to batteries, preventing overcharging and ensuring optimal battery performance.

3.4.2 Converters:

- DC-DC Converters: Convert one level of DC voltage to another, optimizing the voltage levels for different components.
- AC-DC Converters: Convert AC to DC, essential for integrating renewable sources with energy storage systems or DC loads.

3.4.3 Rectifiers:

- Convert AC produced by wind turbines or generators into DC for storage or direct use by DC appliances.

3.5 Control Systems [11-12]

3.5.1 Energy Management System (EMS):

- Centralized control unit that monitors and manages the operation of all components in the HRES, ensuring efficient energy production, storage, and distribution.

3.5.2 Supervisory Control and Data Acquisition (SCADA):

- Provides real-time monitoring, data collection, and control of HRES, enabling operators to optimize performance and quickly respond to issues.

3.5.3 Smart Meters:

- Measure and communicate energy usage and production data, helping to balance supply and demand and optimize energy use.

4. Advantages of HRES

Hybrid Renewable Energy Systems (HRES) represent a significant advancement in the quest for sustainable, reliable, and efficient energy solutions. By combining multiple renewable energy sources, HRES offer numerous advantages that address the limitations of single-source renewable energy systems. The following section outlines the key advantages of HRES. One of the most significant advantages of HRES is the enhanced reliability and stability of energy supply. By integrating different energy sources such as solar, wind, biomass, and hydropower, HRES can balance the intermittency and variability inherent in individual renewable sources. For instance, when solar energy production is low during cloudy days or nighttime, wind energy might be available to compensate, and vice versa. This complementary behaviour ensures a more consistent and stable energy output, reducing the risk of power shortages and enhancing the overall reliability of the energy system. HRES can optimize the use of available resources, leading to improved overall energy efficiency. By coordinating the operation of multiple energy sources, HRES can ensure that each source operates at its optimal efficiency. For example, excess energy generated by solar panels during the day can be stored in batteries or used to power other renewable energy systems, reducing energy wastage [13]. This optimization not only improves efficiency but also minimizes the need for energy storage, which can be costly and resource-intensive. While the initial capital investment for HRES may be higher compared to single-source systems, the long-term cost savings can be substantial. The improved efficiency and reliability of HRES can lead to lower operational

and maintenance costs. Additionally, by reducing the dependency on fossil fuels and minimizing fuel costs, HRES can offer significant economic benefits over time. Advances in renewable energy technologies and economies of scale are also contributing to the decreasing costs of HRES components, making them an increasingly attractive option. HRES offer significant environmental advantages by reducing greenhouse gas emissions and minimizing the environmental impact of energy production. By leveraging multiple renewable energy sources, HRES can reduce the reliance on fossil fuels, leading to lower carbon emissions and air pollution. The use of local and renewable resources also reduces the environmental footprint associated with energy production and distribution. Furthermore, HRES can contribute to biodiversity conservation by reducing the need for large-scale energy infrastructure projects that can disrupt ecosystems. HRES enhance energy security by diversifying the energy mix and reducing dependence on imported fuels. This diversification mitigates the risks associated with energy supply disruptions, price volatility, and geopolitical tensions. By utilizing locally available renewable resources, HRES can promote energy independence and resilience, particularly in remote and off-grid areas where extending the conventional power grid is impractical or uneconomical [14]. This local energy generation capability is crucial for ensuring a reliable energy supply and supporting sustainable development. HRES offer flexibility and scalability, allowing them to be tailored to specific energy needs and geographic conditions. They can be designed to meet the energy demands of various applications, from small-scale residential systems to large-scale industrial installations. The modular nature of HRES enables incremental expansion, allowing for the addition of new renewable energy sources or storage systems as needed. This flexibility makes HRES a

versatile solution that can adapt to changing energy demands and technological advancements.

5. Conclusion

Hybrid Renewable Energy Systems (HRES) represent a significant advancement in the pursuit of sustainable, reliable, and efficient energy solutions. This review has highlighted the critical need for HRES in addressing the limitations of single-source renewable energy systems, such as intermittency and variability. By integrating multiple renewable energy sources, HRES provide a stable and continuous energy supply, enhancing energy security and independence, particularly in remote and off-grid areas. The key components of HRES, including primary energy sources, energy conversion devices, energy storage systems, power electronics, and control systems, work synergistically to optimize energy production and utilization. The advantages of HRES are manifold, including enhanced reliability and stability, improved energy efficiency, significant cost savings, environmental benefits, and contributions to social and economic development.

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