

Standalone Power Generation System using Renewable Energy Sources: A Review

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Abstract - It has become imperative for the power and energy engineers to look out for the renewable energy sources such as sun, wind, geothermal, ocean and biomass as sustainable, cost-effective and environment friendly alternatives for conventional energy sources. However, the non-availability of these renewable energy resources all the time throughout the year has led to research in the area of hybrid renewable energy systems. In the past few years, a lot of research has taken place in the design, optimization, operation and control of the renewable hybrid energy systems. It is indeed evident that this area is still emerging and vast in scope. The main aim of this paper is to review the research on the unit sizing, optimization and energy management of the hybrid renewable energy system components. Developments in research on modeling of hybrid energy resources (PV systems, Wind System), backup energy systems (Battery), power conditioning units (MPPT converters, Buck/Boost converters, Battery chargers) and techniques for energy flow management have been discussed in detail. In this paper, an attempt has been made to present a comprehensive review of the research in this area in the past one decade.

Key Words: Battery energy storage system; Hybrid renewable energy systems Photovoltaic

1. INTRODUCTION

The rapid industrialization over the past three decades due to globalization, inventions in new technologies and increased household energy consumption of the urban population has resulted in the unprecedented increase in the demand for energy and in particular electricity. This has led to a huge supply-demand gap in the power sector. The scarcity of conventional energy resources, rise in the fuel prices and harmful emissions from the burning of fossil fuels has made power generation from conventional energy sources unsustainable and unviable. It is envisaged that this supply-demand gap will continue to rise exponentially unless it is met by some other means of power generation. Inaccessibility of the grid power to the remote places and the lack of rural electrification have prompted for alternative sources of energy. The renewable energy resources, such as wind, sun, water, sea and biomass, have become better alternatives for conventional energy resources.

Hybrid Renewable Energy Systems (HRES) is composed of one renewable and one conventional energy source or more than one renewable with or without conventional energy sources, that works in stand alone or grid connected mode [1]. HRES is becoming popular for stand-alone power generation in isolated sites due to the advances in renewable

energy technologies and power electronic converters which are used to convert the unregulated power generated from renewable sources into useful power at the load end. The important feature of HRES is to combine two or more renewable power generation technologies to make best use of their operating characteristics and to obtain efficiencies higher than that could be obtained from a single power source. Hybrid systems can address limitations in terms of fuel flexibility, efficiency, reliability, emissions and economics. A generalized model of HRES is illustrated with a block diagram in Fig. 1, where either one or both of the renewable sources (solar PV/wind) can be used in combination with back up devices, such as FCs, batteries, UCs or DG sets. Solar PV and wind systems are the primary sources of energy. This energy is available in abundance, but is intermittent in nature and site specific. To overcome this drawback, back up energy devices (secondary sources) are introduced into the system to supply the deficit power and to take care of transient load demands. The primary and secondary sources are connected to the dc bus through dc-dc converters to obtain regulated power output from the sources and to maintain a constant voltage at the dc bus. The converters for PV/wind system are usually a cascade of two dc-dc converters, one used for maximum power tracking and the other for voltage regulation. Similarly, dc and ac loads are connected to the dc bus through dc-dc and dc-ac converters respectively. This ensures regulated power supply to the loads throughout operation. The batteries and UCs are connected to the dc bus via bi-directional dc-dc converters for effective charging and discharging. DG sets are connected by means of ac-dc converters.

The FC stack and electrolyzer need individual dc-dc converters for regulated power output and conversion.

The entire system has one master controller and several slave controllers for different sources. The master controller operates in close co-ordination with all energy sources and slave controllers. It controls the switching action between the primary and back up energy sources depending on availability of power and prior set control logic. The voltage and current measurements of an individual power source are taken locally by respective slave controller and are relayed back to the master controller at each sampling instant.

The slave controller also generates PWM signals for the dc-dc converter under its control and hence monitors the power regulation. The solid black arrows indicate the flow of energy from the sources to the dc bus and from dc bus to loads. The dotted arrow lines indicate the control action and information flow between the sources and controllers. This

HRES ensures continuous and effective delivery of power to the loads. Solar Photovoltaic (PV) and wind energy which are renewable, site-dependent and non-polluting are potential sources of alternative energy. Nonetheless, standalone PV/wind systems can meet the load demand only for the time during which sunshine/cut-in wind speeds are available. Hence, HRES invariably includes backup energy storage systems to meet the load demand at any point of time. The elements of backup energy storage systems are either fuel cell (FC) or battery or diesel generator (DG) or ultra-capacitor (UC) or a combination of these sources. While batteries are most commonly used for this purpose, they typically lose 1–5% of their energy content per hour and thus can store energy only for short period of time [2]. The various possible hybrid system configurations can be designed based on availability of primary energy sources (PV and/or wind) onsite. Backup energy sources are complimentary in nature due to difference in capital and operating costs, power and energy characteristics and fuel flexibility. However, this review is focused mainly on PV based HRES due to space limitations. PV technology is a relatively new field of renewable energy that is rapidly expanding. The amount of power generated by a PV array depends on the operating voltage of the array and the maximum power point (MPP), which vary with solar insolation and temperature. MPP specifies a unique operating point on PV characteristic at which maximum possible power can be extracted. At the MPP, the PV operates at its highest efficiency. Therefore, many methods have been developed to track the MPP [3]. The output power of the solar module is highly affected by the sunlight incident angle and its efficiency can be improved if the solar module is properly installed at the optimum angle. Chen et al. [4] calculated the optimum installation angle for the fixed solar modules based on the genetic algorithm (GA) and the simulated-annealing (SA) method. Significant research on economic and environmental aspects of integrating the PV system with DG has been reported [5–8]. The DG backup for PV systems has gained popularity for quite long time as it is capable of supplying electric energy for 24 h, at low capital cost. However, increased fuel prices, intensive maintenance and harmful carbon emissions from DG sets have made them unsustainable and unattractive [9]. Moreover, the whole system efficiency decreases drastically when the DG has to be run lower than the rated output.

UCs have also been suggested as back up devices for offering high energy density as compared to ordinary capacitors and high power density than batteries [10, 11]. They also have high round trip efficiency (greater than 90%) and can support greater number of charge/discharge cycles.

Over the time, FCs are replacing the DG as an alternative backup energy resource in the integrated PV systems. The major problems associated with FCs are the high cost of the membrane and catalyst as well as fuel availability [12]. However, the combination of the FC and the renewable energy source can provide a multi-fold benefit [13]. First, fossil fuel consumption would be reduced because of higher

FC efficiency than DG, and second benefit would be reduction of power losses, since the FC power plant can be placed at or near the load centre to take advantage of its low noise and emissions. Another important advantage in using FC is its fuel flexibility. However, the most common fuel used is hydrogen. Hydrogen can be derived from natural gas, ethanol, methanol, biogas, and coal gas, propane, naphtha or other similar hydrocarbons through reforming. This type of hybrid system is particularly useful in spaceship, transportation and stationary applications. Hydrogen prices are likely to drop in future to about double price of natural gas as hydrogen is becoming a commodity. The decisive economical factor is the effective cost per kWh. Today's FCs are already competitive in comparison to DG, offering a huge up-side potential with the expected cost decrease in hydrogen and cost increase in diesel. If the whole system is properly designed, then FC results in reduced maintenance effort and cost compared with a DG [14].

The review article discusses four main aspects in the subsequent sections, i.e. unit sizing and optimization of the HRES, modeling of the major components used in hybrid PV systems with Battery and WT system. The sizing and optimization study is essential before setting up or installation of a HRES. It gives a fair idea of the size of the individual components and hence plays an important role in the initial capital investment.

The modeling of components is highly significant in understanding the physical mechanisms and power generation ability of the components. It is useful for simulation studies. The optimal energy flow study devises techniques and schemes to operate the system at minimum cost but with high reliability. Lastly, the challenges bring forward the gaps in research areas and the discussion on future trends is vital for improving the overall technology of the HRES.

2. Unit sizing and optimization

Renewable energy sources essentially have random behaviour and cannot have accurate prediction. Continuous sunny days give abundant PV power because of which the battery banks or hydrogen tanks are underutilized. On the other hand, cloudy days with continuous rain can discharge the batteries and hydrogen storage tanks well beyond the lower discharge limit. Therefore, the number of PV modules to be installed, the size of the FC, battery bank and hydrogen storage tanks need to be calculated carefully considering all extreme weather conditions. Unit sizing and optimization is basically a method of determining the size of the hybrid system components by minimizing the system cost while maintaining system reliability. Optimum resource management in a hybrid generation system is crucial to achieve acceptable cost and reliability level. These design objectives are usually conflicting with one another and thus a reasonable trade off between them is desirable.

Over sizing the system components will increase the system cost whereas under sizing can lead to failure of power supply. Thus, sufficient care should be taken to design a reliable system at minimum cost.

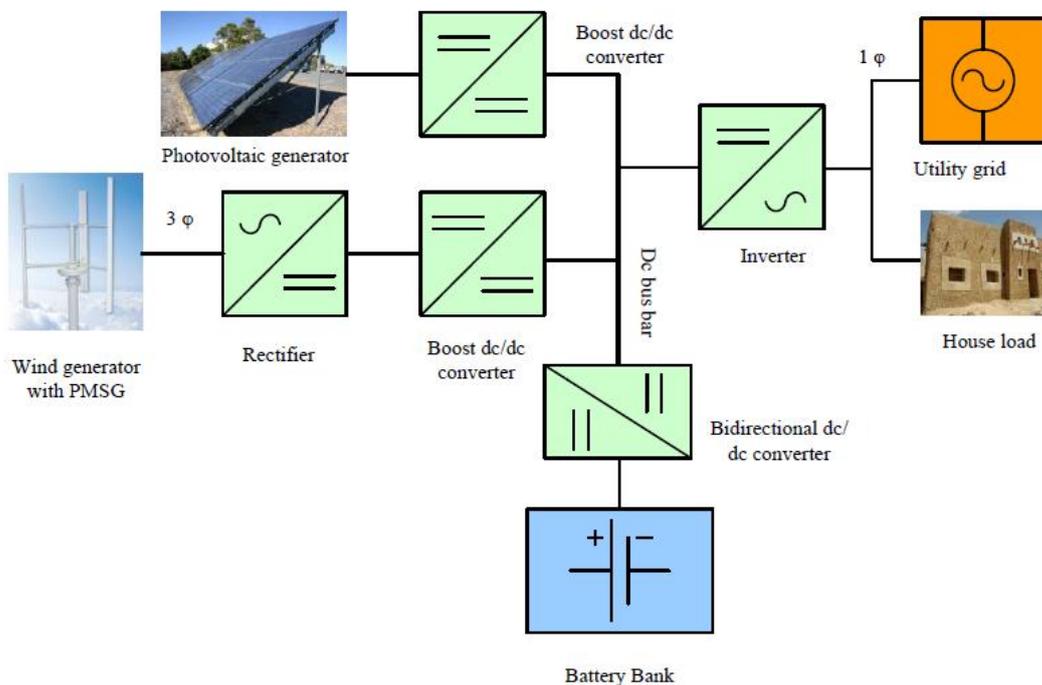


Figure 1 Schematic for the system

A classification chart that groups and classifies the various sizing procedures is illustrated in Fig. 2. This broad classification is based on the availability and non-availability of weather data, such as irradiance, clearness index and wind speed [15]. When weather data is available, conventional sizing approaches are used and are classified on the basis of concept of energy balance and reliability of supply. However, conventional techniques need long term meteorological data for sizing of PV systems, which may not be available in remote isolated sites. Thus, non availability of weather data in remote sites has urged the researchers to look into Artificial Intelligence (AI) techniques, such as Artificial Neural Networks (ANN), Fuzzy Logic (FL), Genetic Algorithms (GA) or a hybrid of such techniques [16]. Conventional sizing methods are in use for more than two decades and give accurate results when actual weather data is available. One of the simple ways of sizing components is based on the concept of energy balance. The daily average available energy from the sun and the daily average load demand are balanced to determine the number of modules needed. The available energy from the sun can be determined from solar irradiance data. Sizing based on energy balance takes into consideration the path losses and efficiencies of the source, converters and controllers. Li et al. [17] proposed an algorithm to determine the minimal system configuration using an iterative technique based on energy balance. The optimal sizes of the system components for a hybrid PV/FC/Battery system producing onsite hydrogen were determined in [18]. Sizing of batteries were

done by carefully choosing the days of autonomy, a vital parameter in battery sizing. FC and electrolyzer sizing were done taking marginal safety.

Some of the sizing procedures in the literature consider the reliability of electricity supply as an important factor. This reliability is determined by estimating the loss of load probability (LOLP) which is the ratio between estimated energy deficit and the energy demand over the total time of operation [15]. Other similar concepts are loss of power probability (LOPP), loss of power supply probability (LPSP) and load coverage rate (LCR). Such sizing techniques are used in applications where a high degree of reliability is required. Ardakani et al. [19] used a reliability index called equivalent loss factor (ELF) for optimizing the size of the components in a hybrid wind/PV/Battery system. Xu et al. [20] proposed a strategy to minimize the total system cost subject to the constraint of LPSP using GA. Moriana et al. [21] also used LPSP as a reliability index for sizing the storage unit in a wind/PV system.

Nelson et al. [22] considered an LPSP less than or equal to 0.0003, which corresponds to a loss of power of 1 day in 10 years for sizing the PV modules and hydrogen tanks in a wind/PV/FC system. In remote inaccessible sites, weather data collection is difficult.

Hence researchers devised AI based techniques to size the PV systems. Mellit et al. [16] discussed various AI methods for sizing of PV systems. Some of the AI techniques are ANN, FL, GA or a hybrid of such methods. These methods can tolerate certain degree of error in the input data; generate

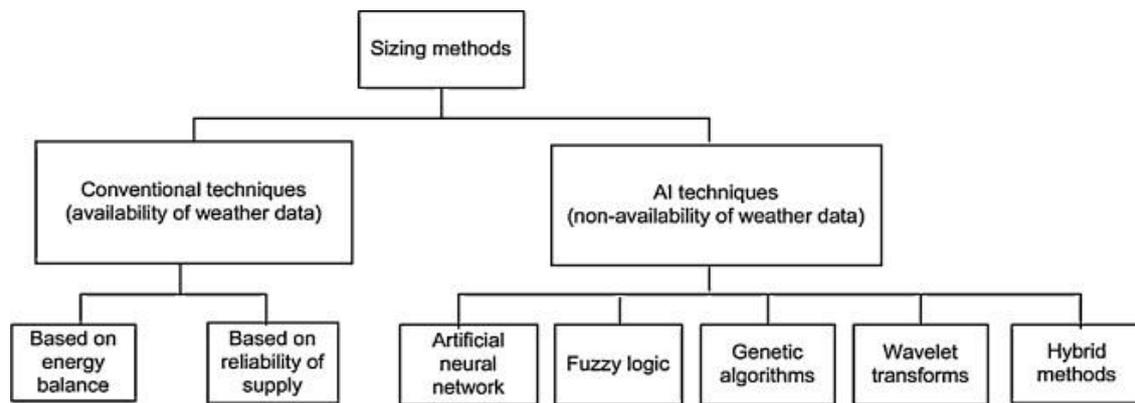


Figure 2 Classification of hybrid system sizing methods

fast results once trained from examples and model complex non-linear processes with ease. ANN is a collection of interconnected processing units where each incoming connection has an input value and a weight attached to it. The output is a function of the summed units. ANNs can then be trained with respect to data sets, and once trained, new patterns may be presented to them for prediction or classification. FL allows the application of a 'human language' to describe the problems and their fuzzy solutions. When input parameters are highly variable and unstable, fuzzy controllers can be used as they are more robust and cheaper than conventional PID controllers. Hybrid methods use a combination of two or more AI techniques for sizing the system. Mellit et al. [23] considered the latitude and longitude of the site as inputs and estimated two outputs based on an ANN model for sizing the PV system. The output parameters allowed successful sizing of the number of PV modules and batteries with a relative error less than 6%. Similar applications of various AI techniques in sizing and optimization of HRES are listed in Table 1.

Table 1. AI techniques used in sizing of HRES

Sr. No.	AI techniques used and reference	Brief description
1.	Genetic algorithm(GA)[20,24,25]	Optimal sizing of standalone hybrid wind/PV systems and wind/PV/DG systems
2.	Artificial neural network (ANN)[23,26]	Sizing PV system using adaptive ANN
3.	Hybrid Methods	Sizing of standalone PV system using neural network and wavelet techniques

Sizing of the components is generally accompanied by optimizing the system components or other parameters, such as investment cost, output energy cost or consumption of fuel [29]. Optimization is generally carried with the objective of minimizing the Net Present Cost (NPC) or by minimizing the levelized Cost of Energy (LCE) [30]. Wang

and Singh [31] proposed a constrained mixed-integer multi objective particle swarm optimization (PSO) method to minimize the system cost and simultaneously maximize the system reliability. The unit sizing and optimization by minimizing the NPC using HOMER for a hybrid PV Wind Diesel-Battery system and hybrid PV-Diesel-Battery system has been carried out in [32] and [33], respectively. Ashok [34] used non-linear constrained optimization techniques to minimize the annual operating cost for a hybrid PV-Wind-Diesel-Battery system including a micro-hydro. The renewable energy fraction was calculated to be 100% and the need for DG was hence eliminated.

Several simulation tools are readily available today in order to model, size and optimize the hybrid system. An overview of such simulation and/or optimization tools is discussed in [29, 30].

4. Optimal energy flow management in hybrid systems

An optimal energy flow management among the various energy sources in HRES is necessary since, the power output from renewable sources is intermittent and dependent on several uncontrolled conditions. The dynamic interaction between various energy sources and the loads often requires a careful study of the transient response of such systems. The energy management strategy should ensure high system efficiency and high reliability with least cost. The main objective of the technique should be to supply the peak load demand at all times. In hybrid PV systems, FCs serve as long term energy storage option and are in demand because of multiple advantages [34,35]. However the slow dynamics of FCs and its degradation due to frequent start-up and shut down cycles is a major disadvantage. Hence batteries are used in such hybrid systems to take care of power deficits and to act as a short term energy storage medium. The combination of FCs and batteries along with PV helps in ensuring uninterrupted power supply to the load. The key parameters that influence or help in deciding the optimal energy management strategy have been summarized as follows:

- Useful electrical energy available from the primary renewable energy sources, such as solar PV and wind turbines.
- Capital cost, operating cost, lifetime and days of autonomy of storage devices, such as batteries, ultra-capacitors and FCs.
- State of charge of storage devices or the pressure level of hydrogen tanks in case of hydrogen energy systems.
- The number of start-up and shut down cycles for FCs and electrolyzer.
- Fuel price in case of hybrid systems involving DG.

The literature on energy management schemes is quite extensive and includes various configurations of the hybrid systems involving solar PV. Ipsakis et al. [36] proposed three power management strategies (PMS) for a hybrid PV/Wind/FC/Battery system with hydrogen production using electrolyzers. The PMSs are compared based on a sensitivity analysis by considering several parameters such as SOC of batteries and output power from FC.

The key decision factors in the PMSs are the power delivered by the renewable energy sources and the SOC of the batteries. These PMSs strongly affect the lifetime of various subsystems, mainly the FC and electrolyzer. Three stand-alone hybrid PV systems (PV/Battery, PV/FC, PV/FC/Battery) using different energy storage technologies are discussed, analysed and compared in [17]. The energy management strategy here is based on the system energy balance throughout the year and a trade-off between maximum system efficiency and minimum system cost has been implemented. The PV/FC/Battery hybrid system was found to have higher system efficiency with lower cost and also required lesser number of PV modules as compared to the other two configurations.

Kang and Won [37] suggested a PMS for a PV/FC/Battery hybrid system based on the cost of battery and FC. The authors have aimed at reducing the number of change over between FC and battery by introduction of measuring and time delay elements to the conventional strategy. Jiang [38] presented an effective energy management strategy and simulated in virtual test bed (VTB) environment for a PV/FC/Battery system connected to the dc bus through appropriate dc-dc power converters and controls. The PV-Battery subsystem was controlled in two modes, namely the MPPT mode and the bus (battery) voltage limit (BVL) mode. The BVL mode prevents the battery from overcharging and the MPPT mode draws maximum power from the PV module. Similarly, another control strategy was designed to manage the FC output current through a boost converter and regulate the bus (battery) voltage by a PID controller.

Some studies on hybrid PV systems have also considered the use of UC instead of batteries [11,39]. Uzunoglu et al. proposed a control strategy for a hybrid PV/FC/UC system. The UC bank stores the excess energy from PV and delivers it to the load when the FC is operating at its lower limit. The UC bank compensates the tracking mismatches and delays of the FC system, which generally exhibits a slower response. A

similar strategy is suggested in [40], but the primary source of power is provided from both solar PV and wind.

Dispatch strategies for a PV/DG/Battery system based on set point values of system load and battery SOC has been proposed in [38] and an optimum set of points for starting and stopping the DG were determined. An operational control of PV/DG/Battery hybrid system to minimize the cost of fuel and storage capacity of battery has been proposed by Park et al. [41]. The authors have suggested six operating modes where the DG is either switched off or operates between constant output/maximum output depending on the battery storage energy.

5. Challenges and future trends in HRES

HRES have come a long way in terms of research and development. However, there are still certain challenges in terms of their efficiency and optimal use. The challenges faced by the developers are following:

- The renewable energy sources, such as solar PV and FCs, need break-through technology to harness more amount of useful power from them. The poor efficiency of solar PV is a major impediment in encouraging its use.
- The manufacturing cost of renewable energy sources needs a significant reduction because the high capital cost leads to an increased payback time. Cost reduction will provide an incentive to the industry to implement such systems.
- The losses involved in power electronic converters have been reduced to a satisfactory level; however, it should be ensured that there is minimal amount of power loss in these converters.
- The storage devices, such as batteries and UCs, need to increase their life-cycle through innovative technologies.
- Generation or storage of hydrogen is very expensive and energy intensive currently. There is a need of alternatives like fuel reformers based on easily available and low cost fuels.
- The implementation of HRES involves certain protection issues; hence, suitable protection devices need to be installed for safety. Moreover, introducing these distributed generators will require an up gradation in the existing protection schemes.
- These standalone systems are less adaptable to load fluctuations. Large variation in load might even lead to entire system collapse.
- The disposal of storage devices, such as batteries and hydrogen tanks and safety concerns regarding the storage of hydrogen, is a major concern for the manufacturers.

Thus the researchers and engineers need to find solutions to address the above mentioned problems. Future research and development efforts can enhance the use of renewable energy sources. Improved technology and demand for renewable energy can help in reducing the cost to an extent comparable with conventional energy. Effective and optimum use of the energy sources in standalone systems can help in meeting the energy demands of remote,

inaccessible areas and make them self sufficient. Government can provide carbon tax benefits to promote the use of renewable energy. More incentive based policies promoting the establishment of renewable power plants should be rolled out by the Government.

This will not only encourage the use of renewable energy but will also ensure a clean and bright future for the coming generations. Throughout the world, energy policy is developing rapidly with the aim of providing electrical energy supplies that are low or zero carbon to reduce the production of greenhouse gases and mitigate climate change. These objectives converge in the use of distributed generation: renewable and cogeneration. HRES hold promising applications in terms of distributed generation. They can be used as an alternative to grid-connected systems in remote inaccessible sites. Power can be generated based on the demand at any particular site depending on the availability of resources. This will not only reduce the grid dependence but also help us in reducing the emission levels globally. The eco-friendly nature of hybrid renewable energy systems is a major driving factor which has enhanced its application on a large scale.

6. Conclusions

This review article presents comprehensive overview of hybrid renewable energy systems (HRES) with emphasize on solar photovoltaic based stand-alone applications. Various significant aspects of such systems, such as unit sizing and optimization and optimal energy flow management strategies, are specifically reviewed. Different sizing techniques have been reviewed under classification based on availability of weather data. Developments in research on modeling of hybrid energy resources (PV systems), backup energy systems (fuel cell, battery, ultra-capacitor, diesel generator) and power conditioning units (MPPT converters, buck/boost converters, battery chargers) have been reviewed. The equivalent models including several physical mechanisms of these system components have been extensively discussed with a broad classification in modeling section. The section on energy flow management has covered significant references on various methods for optimal operation and control of HRES.

The issues on economic viability and grid interconnection are the major challenges to make the HRES adaptable and sustainable. The high capital cost and low demand in solar photovoltaic and fuel cells had slowed down the large scale implementation of such hybrid systems in the past. However, recent global boost to renewable energy markets has dramatically encouraged research and development in this sector. Future trends include cutting edge technology development to increase the efficiency of such hybrid systems and encouragement in terms of its implementation. HRES has an immense potential to meet the load demand of remote, isolated sites and can contribute significantly to both rural as well as urban development. This in turn reduces the central generation capacity and increases overall system reliability. These units can supply uninterrupted power at

zero emission level which is the major advantage of such systems. The widespread use of hybrid renewable energy systems will not only solve the energy issues but also ensure a green and sustainable planet.

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