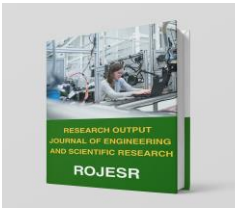

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Hybrid Energy Systems for Off-Grid Communities

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ABSTRACT

Hybrid energy systems (HES) integrating solar, wind, and bio-diesel power are increasingly recognized as effective solutions for off-grid communities. These systems offer enhanced resilience and reliability by combining multiple energy sources, thereby mitigating the risk of power shortages due to the intermittency of individual renewable sources. This paper examines the components, challenges, and design considerations of HES, emphasizing the importance of energy storage technologies and system optimization. Case studies from various regions illustrate the practical applications and benefits of hybrid systems in ensuring a sustainable and uninterrupted power supply for remote and rural communities.

Keywords: Hybrid energy systems, off-grid communities, renewable energy, solar power, wind power.

INTRODUCTION

Hybrid energy systems are becoming a solution of choice for off-grid communities. Solar, wind, and bio-diesel offer not only clean energy solutions but also added resiliency with the ability to generate power from multiple sources. This helps ensure that homes, businesses, and whole communities are not cut off from vital power supplies because of mechanical failures, as well as go further in offering both on-grid and off-grid solutions [1]. We will discuss the whole systems approach to energy storage and secondary power generation to smooth variability in renewable power supplies and ensure we can provide quality, reliable, and affordable power – the first requirement of the Interim Report from the Tesla/SA Power Networks micro-grid in South Australia released facilitated by the Distributed Energy Resource Alliance. We will detail how with optimal renewable solutions there is a smaller requirement for backup power, along with its associated lower costs, and potential sell-back requirements that grow the customer-sized and behind-the-meter storage system market for houses, for business, and for full communities. It will cover a commentary on the risks in current systems facing communities and the consequences of recent power blackouts in different Australian regions. So far in 2016, multi-day power blackouts have had a greater economic impact on the local communities than foreign tariff cuts, other international trade issues, and high-profile car manufacture closure announcements [2].

CHALLENGES IN OFF-GRID ENERGY SYSTEMS

Power and energy are the most important ingredients for running multiple household and industrial appliances. The expanded production and utilization of advanced power systems have increased the power demands. Every quarter of the globe has a different nature of the seasons, which results in wide variations in the intensity of the solar energy resource. Intermittency of this source is a basic concern that has to be overcome for its effective and efficient use. The intermittency of wind may vary more than the sun. Energy storage and fossil fuel backup generators are the most widely used techniques for this concern. Both of the techniques have different operational related problems. Only the energy storage method can give pollution-free and uninterrupted power supply. Thus, it can be concluded that there is no single source available that may produce an uninterrupted power supply. Only a combination of different sources may become the ultimate solution [3]. The rapidly growing economic power of scarcely populated remote areas makes the investment in the expansion of the smart grid infrastructure an inadequate business plan. Due to the gradual depletion of economic resources, faraway areas are still suffering from low-quality power generation sources like petrol generators. Due to the low-quality power source, demands of local people are still unmet. On the contrary, solar and wind energy resource bases are quite enough for economic and uninterrupted power supply. RTAL power production and distribution infrastructure is a vast and authorized project supported by several big organizations working both in the research area and solar-wind energy resource promotion in many African areas. In these contexts, this paper describes the state-of-the-art energy systems specifically those which use only one energy resource for power production, their impacts, and benefits. It gives a general overview of the energy systems which can use more than one energy source and are capable of an intelligent mode of working. Energy storage technologies are also discussed in this paper [4].

INTERMITTENCY OF RENEWABLE SOURCES

Energy in remote settings, such as off-grid communities, islands, and rural areas, has traditionally focused on utilizing diesel generators. However, with the advent of technological advancements, renewable sources such as solar, wind, and hydro are being used in favor of fossil fuels to impact several aspects, including the feasibility and social considerations associated with their emissions, and the prospect of increasing the public acceptance of hybrid systems. Renewable energy sources are constantly available; however, they come with their limitations, such as resource availability intermittency [5]. Intermittency has been recognized as the major drawback of renewable power systems. As a result of such transiently changing availability, there is a more or less transient over/under generation of energy from RES. For a community connected to a public grid, the management of this situation implies that the grid will act as a 'buffer'. The intermittency issue affecting the energy supply to the connected user is then solved by the TSO, and it remains very well hidden from the end user. For a community located away from any public grid, the management of this situation is totally different. If the intermittency produced cannot be 'buffered', then it is directly provided to the community with a huge impact. Hence, no single technology yields anywhere near a reliable power supply required for a sound end-user community or industrial application. The situation is the same whether one considers only one single intermittent source or a set of them, as the production of the overall system only increases if the intermittency of the different sources is decorrelated. If a truly twenty-first-century power supply for off-grid communities, both in the industrial and emerging economies, is to be considered, then solutions to this intermittency issue must be found and become a focus of study. Even in grid-connected situations, these are issues of immediate practical importance [6].

ENERGY STORAGE TECHNOLOGIES

The effective and efficient utilization of renewable energy in off-grid energy systems requires robust and durable energy storage devices. This is extremely important where energy demand does not match energy consumption, such as solar power systems during rainy or winter days. Energy storage systems (ESS), therefore, are a crucial component in the power infrastructure. A hybrid system consists of two or more renewable power sources, along with an ESS. These ESSs can be installed individually for each renewable energy, or together in a single storage system. With the development of many storage technologies, including advanced high energy and power density capacitors and batteries, it is now becoming possible to properly store energy for off-grid and remote applications [7]. As energy storage devices in renewable off-grid power infrastructure, many storage technologies can be carefully selected to store energy, from the green "Flow" batteries, the highly efficient lithium-ion technology, up to the conventional deep cycle lead-acid batteries. A brief and detailed overview of the energy storage and battery technologies is shown in this text, to review some of the features of various energy storage technologies (as shown in Table 1). Taking into consideration cost, lifespan, energy and power density, efficiency of use, the Peukert Effect, as well as the batteries' energy density. A preference score from 1-10 is given to each energy storage system, and based on their strengths, they are rated as having good, average, or poor performance in off-grid systems. These are approximations, with the selection of battery technology strongly reliant on the application. LiFePo batteries have been shown to be a strong VRE storage technology [8].

COMPONENTS OF HYBRID ENERGY SYSTEMS

Various types of power sources, both renewable and non-renewable, are used to generate power. In isolation, however, the majority of these power sources are unable to meet the necessary power supply requirements. The entire solar grid system employs a variety of renewable or never-ending sources which have a ton of potential in the production of power. The off-grid hybrid system consists of a variety of resources that are frequently utilized in tandem to generate power. Such off-grid hybrid systems have the potential to generate more power than can be used if two or more resources are employed, such as a solar power supply with a windmill. A battery backup is controllable in the off-grid hybrid solar system [9]. The main components of hybrid energy systems are solar photovoltaic (PV) arrays, wind turbines, battery storage systems, and power electronics (inverters and controllers). A power conditioning unit is often used in hybrid energy systems. However, the exact nature of the power conditioning may vary depending on the specifics of the particular hybrid energy system in question. For example, based on the type of solar PV array and wind turbine, the power in the hybrid system may be received at a medium voltage (MV) level, and a step-up transformer will be employed to increase the voltage of the power from the MV level to the extra high voltage (EHV) level. The wind and solar power will then be dedicated to charge the battery. Because the power produced by the solar PV array and wind generation systems is typically highly variable and unreliable, special power electronics control is required. These components serve to connect the energy systems to the main grid and to ensure energy reaches customer facilities. They are also shielded from energy generation variations and outages. They are designed to work at multiple performance points, provide a high-performance level, and control power flow. Over the years, various types of inverters and their enhanced technologies have been developed and tested, with grid-connected inverter technology largely standardized, while battery-based inverters used in off-grid systems still require more development [10].

SOLAR PHOTOVOLTAIC (PV) ARRAYS

Solar photovoltaic (PV) arrays are the primary energy conversion technology in hybrid energy systems. By using radiation from the sun, PV panels generate electricity that can be stored within the system for future use or distributed for immediate use. Operationally, PV arrays exhibit high reliability: upon reaching the end of their operational lifetime, usually 30 years, they require close to zero resources to dispose of. Finally, PV arrays require little maintenance with minimal operating costs [11]. Having gained economical financial support, investment subsidies, and technological advancements, solar PV has been spreading globally in standalone and hybrid systems, reducing emissions in off-grid and remote areas. Although offering great advantages over other renewable technology, the main disadvantages of this technology are linked to the variability of solar radiation and the size of storage and backup systems required to balance the fluctuations of sunshine. Smets et al. analyzed the solar resource and social/hydrological conditions to perform a detailed modeling of the off-grid PV system, addressing six different dimensions. They demonstrated that better energy production during the dry season is guaranteed at 10°. However, because the rainy season is still present at 10° compared to the equator, the additional production cost and system investment are not viable. In order to reduce these effects and increase off-take solar power, use storage and backup. Based on economic analysis, they found that batteries reduce yearly diesel consumption by 60 to 94% while providing backup power [12].

WIND TURBINES

Wind turbines are mechanical devices for converting kinetic energy in the wind into mechanical work. They are generators that produce electrical energy. The essential components of a wind turbine are the rotor, a mechanical transmission, and the generator, which in most cases is a permanent magnet synchronous generator (PMSG). The rotor of the turbine contains a number of blades, which can range in number from just one to over one hundred, with three or four blades being typical for horizontal axis wind turbines, which are the most common design. The axis of rotation of the rotor is coplanar to the plane of the blades, which gives the horizontal axis machine its name [13, 14]. Wind turbines have become popular in recent decades as sources of electrical power. Their merit lies in their modular nature, the rapid advance of technology, encouraging cultural acceptance, and relatively little invasive land use. Wind energy performance is linked to the cube of wind velocity at the turbine sites. This makes for a high sensitivity to wind speed. At the beginning of a wind mapping study, the local annual energy matrix data will often show large fluctuations, since no smoothing has been applied. When trying to sight a wind farm (WF), it is more than necessary to have clear and statistically relevant wind speed data. Unfortunately, it is not cost-effective to run continuous air-vane logging for a long period of time in any and all proposed WF sites. As far as there is no solar and biomass resource from studies, one can also conclude that the wind segment is paramount for these off-grid communities [15]. In sum, wind power is better suited for near off-grid communities and it is a better fit than for urban application. A rural community far from the power grid might be a possible application, although other renewables (solar and hydroelectric) are also to be studied. Mini and micro wind turbines will be assumed for the communities of this section. These will be demonstrated to require explicit wind mapping and flow models. Moreover, the terms for basic prediction and applications are also provided [16].

BATTERY STORAGE SYSTEMS

Energy storage plays a significant role in hybrid energy systems for off-grid communities. It decouples the energy generation from its use on the demand side. During the period of low demand, the surplus generated power can be stored in a battery for use at a later time or when the generation is not available. The grid-connected energy generation and storage could ensure reliable power supply. The battery bank is the most commonly used storage system used in hybrid energy systems. However, the best storage technology and size of the battery storage depend on the dynamics of the renewable energy resource, the load requirement, and the economics of the system. The batteries used in stand-alone hybrid power systems have a number of features, including deep discharge, long cycle life, low maintenance, and high efficiency in charging and discharging [17]. Batteries play an important role in remote hybrid energy. Batteries are required to store energy, so that the PV itself will work when needed. Ni-Fe, Li-ion, NaS or VRLA batteries are used in the system. Batteries are widely used in an off-grid hybrid system, in situations where there is no wind and little sunshine. The replacement of energy storage is essential in the contemporary options for remote area electrification through hybrid systems. The use of batteries for storage is expected to decline from 52.1% to 45.7%. As shown, PHS will dominate for energy storage in remote off-grid systems. It is deduced that while iron electro-chemical-based storage technologies are currently in practice [18].

DESIGN CONSIDERATIONS FOR HYBRID ENERGY SYSTEMS

One common mistake in the design of off-grid energy systems is the "first cost fallacy" where people give too much importance to the capital cost of the system while overlooking the cost of the ongoing maintenance and repair. An equally damaging mistake is to make overly optimistic assumptions about future fuel prices. If energy costs are going to rise faster than interest rates, a system that is somewhat less expensive in the long term is potentially more attractive than a capital-cost optimized system. Another common mistake is under-sizing components due to concerns about initial cost. The confirmation that "system undersizing has resulted in unreliable, often down for substantial periods of time, systems which have sometimes been abandoned" has been reached by multiple investigators over many years [19]. It is also important that the system is optimally sized. Oversizing components can result in inefficient operation during a large portion of the year when the renewable energy supply predominates. The incorporation of some conventional generating capacity with a lower capacity factor can, in some cases, be cost justifiable if it increases the overall system efficiency. One of the most important lessons about off-grid wind systems from the widespread experience in Australia has been the need for good instrumentation and monitoring if the system is not to suffer avoidable downtime because of freezing (or otherwise fouled) anemometers, burned-out charge controllers, etc. Even good old car batteries should be monitored [20, 21].

SIZING OF COMPONENTS

The selection and sizing of the various components used in the hybrid energy systems are critical because the performance and reliability of the entire systems depend on this. In large scale implementations, optimization methods and computer software have been developed and used to provide the best possible solution. This is done by ensuring that the sizing process finds an economically acceptable compromise aimed at a minimal use of non-renewable energies and distribution infrastructure while increasing reliability, reducing the levelized cost of energy, etc. The approaches to the sizing of the various system components have been drastically reviewed over the years, providing more accurate results because of better understandings of renewable resources [22, 23]. The sizing of the diesel generator is based on the electricity demand that has to be met in the absence of renewable resources in order to ensure electric power supply to the end-users. In an off-grid situation, the size of the generator is the minimum size of all generators that should be used in the event where a single generator is required to meet the electricity demand. The goal of the sizing of the energy storage system is to minimize its size so as to reduce its initial cost. According to the system operator, there should be enough energy storage capacity to ensure that 99.9% of the energy generated by the renewable sources is dispatched, while it is stated that the energy storage should be designed to support full electricity supply security to end-users (100%) [24].

SYSTEM CONTROL AND MONITORING

One of the most critical aspects of any hybrid system, including HE systems, is the control of various components so that they work stably and efficiently with energy sources. A control strategy (or energy management strategy) for the real-time operation of a hybrid system under different operating conditions is necessary. The objective of the control strategy is to properly manage and switch between the generator and energy storage to provide the load with the necessary power, as well as to manage energy coming from PV/WPS/TP. Different control strategies have been proposed and employed for sizing, planning, testing, and optimizing the operation of a microgrid. However, the control objective and constraints imposed on different systems vary. The most widely employed method is a centralized (or distributed) energy-management system (EMS), which can be further classified as a rule-based method, a fuzzy logic method, PID, neural-fuzzy methods, artificial neural network (ANN), expert systems, genetic algorithms (GAs), mixed integer linear programming (MILP), and HOMER [25]. Real-time performance monitoring is desired to ensure reliable operations and the successful management of energy generation, storage, and transfer. It is important to monitor both the functioning of the different elements (energy consumption, PV generation, WPS/TP production and usage) and the evolution of storage levels of batteries, hydrogen, and water in the different tanks to ensure the reliability of the system. Ethnographic research is carried out to ascertain user preferences for monitoring systems. Users' feedback is valuable for designing monitoring systems that are effective in the local context and can monitor the poverty level of the inhabitants and access some basic services [26].

CASE STUDIES OF HYBRID ENERGY SYSTEMS IN OFF-GRID COMMUNITIES

Solar-wind generation systems

Some communities in Bolivia rely on home solar-wind battery hybrid systems for electricity generation. Hybrid PV-wind systems for rural electrification applications are considered an attractive solution because energy generation can be continuous throughout the day by configuring the systems in appropriate ways, reducing the need for large storage capacities and providing a more reliable energy supply. A hybrid photovoltaic and wind turbine system is also likely to have a more constant power output than by singly using wind and solar systems. The systems that have been implemented in the pilot micro-solar-wind hybrid projects in this region also integrate backup batteries and advanced power electronics to assemble power and generate electricity in quantities to spare for distribution and industrial use, combining off-grid electricity generation with commercial, medium-scale energy storage [27].

Combustion engine (diesel or petrol) and renewable resources

The most common hybrid electricity generation systems in developing regions are those that use a combustion engine (either diesel or petrol) and a wind turbine or micro-hydro plant. PV panels are often included with the other renewable resource because they have become cheaper in recent years and are now considered as low-cost options, due to their rapidly declining pricing. These hybrid systems are typically used to supply between around 10 and 50 rural families, or mains electricity to a telecommunications repeater, pump water for local communities and irrigation schemes, or light up a visitor centre in isolated regions where grid extension is cost-prohibitive. Hybrid PV-diesel systems are also made use for supplying power at the base of mobile phone masts where no grid electricity is available, or in stand-alone mini-grids to cover telecommunication or water needs, but not households. Diesel energy systems (DESs) are commonly part of a mini-grid that integrates power generation from renewable resources [28].

CONCLUSION

Hybrid energy systems represent a promising solution for providing reliable and sustainable power to off-grid communities. By integrating multiple renewable energy sources and advanced energy storage technologies, HES can address the intermittency issues associated with individual renewable sources, ensuring a stable power supply. The successful implementation of these systems requires careful consideration of component sizing, system control, and real-time monitoring to optimize performance and reduce costs. The case studies demonstrate the potential of HES to improve the quality of life in remote areas, highlighting the importance of continued research and investment in these technologies to achieve widespread adoption and long-term sustainability.

REFERENCES

1. Arif S, Taweekun J, Ali HM, Ahmed A et al. Building Resilient communities: Techno-economic assessment of standalone off-grid PV powered net zero energy (NZE) villages. Heliyon. 2023. cell.com
2. Burger C, Froggatt A, Mitchell C, Weinmann J. Decentralised energy. 2020. ubiquitypress.com
3. Asiaban S, Kayedpour N, Samani AE, Bozalakov D, De Kooning JD, Crevecoeur G, Vandevelde L. Wind and solar intermittency and the associated integration challenges: A comprehensive review including the status in the Belgian power system. Energies. 2021 May 4;14(9):2630. mdpi.com
4. Javed MS, Ma T, Jurasz J, Canales FA, Lin S, Ahmed S, Zhang Y. Economic analysis and optimization of a renewable energy based power supply system with different energy storages for a remote island. Renewable Energy. 2021 Feb 1;164:1376-94. academia.edu
5. Baz K, Cheng J, Xu D, Abbas K et al. Asymmetric impact of fossil fuel and renewable energy consumption on economic growth: A nonlinear technique. Energy. 2021. [HTML]
6. Hosseinzadeh N, Aziz A, Mahmud A, Gargoom A, Rabbani M. Voltage stability of power systems with renewable-energy inverter-based generators: A review. Electronics. 2021 Jan 7;10(2):115. mdpi.com

7. Zebra EI, van der Windt HJ, Nhumaio G, Faaij AP. A review of hybrid renewable energy systems in mini-grids for off-grid electrification in developing countries. Renewable and Sustainable Energy Reviews. 2021 Jul 1;144:111036. sciencedirect.com
8. Gourley SWD, Brown R, Adams BD, Higgins D. Zinc-ion batteries for stationary energy storage. Joule. 2023. [HTML]
9. Amara S, Toumi S, Salah CB, Saidi AS. Improvement of techno-economic optimal sizing of a hybrid off-grid micro-grid system. Energy. 2021. [HTML]
10. Hassan Q, Jaszczur M, Abdulrahman IS, Salman HM. An economic and technological analysis of hybrid photovoltaic/wind turbine/battery renewable energy system with the highest self-sustainability. Energy Harvesting and Systems. 2023 Nov 8;10(2):247-57. degruyter.com
11. Bonthagorla PK, Mikkili S. Performance investigation of hybrid and conventional PV array configurations for grid-connected/standalone PV systems. CSEE Journal of Power and Energy Systems. 2020 Oct 6;8(3):682-95. ieee.org
12. Deevela NR, Singh B, Kandpal TC. Techno-economics of solar PV array-based hybrid systems for powering telecom towers. Environment, Development and Sustainability. 2021 Nov 1:1-27. [HTML]
13. Rekioua D. Wind power electric systems. 2024. [HTML]
14. Wilberforce T, Olabi AG, Sayed ET, Alalmi AH, Abdelkareem MA. Wind turbine concepts for domestic wind power generation at low wind quality sites. Journal of Cleaner Production. 2023 Mar 25;394:136137. [HTML]
15. Ge M, Gayme DF, Meneveau C. Large-eddy simulation of wind turbines immersed in the wake of a cube-shaped building. Renewable Energy. 2021. [HTML]
16. Tsiaras E, Papadopoulos DN, Antonopoulos CN, Papadakis VG, Coutelieris FA. Planning and assessment of an off-grid power supply system for small settlements. Renewable Energy. 2020 Apr 1;149:1271-81. [HTML]
17. Schöne N, Khairallah J, Heinz B. Model-based techno-economic evaluation of power-to-hydrogen-to-power for the electrification of isolated African off-grid communities. Energy for Sustainable Development. 2022. researchgate.net
18. Kumar PP, Saini RP. Optimization of an off-grid integrated hybrid renewable energy system with different battery technologies for rural electrification in India. Journal of energy storage. 2020. [HTML]
19. Zhang Z, Ding T, Zhou Q, Sun Y, Qu M, Zeng Z, Ju Y, Li L, Wang K, Chi F. A review of technologies and applications on versatile energy storage systems. Renewable and Sustainable Energy Reviews. 2021 Sep 1;148:111263. [HTML]
20. Simshauser P, Billimoria F, Rogers C. Optimising VRE capacity in renewable energy zones. Energy Economics. 2022. [HTML]
21. Aktaş A. The importance of energy storage in solar and wind energy, hybrid renewable energy systems. Advances in clean energy technologies. 2021. [HTML]
22. Xu X, Hu W, Cao D, Huang Q et al. Optimized sizing of a standalone PV-wind-hydropower station with pumped-storage installation hybrid energy system. Renewable Energy. 2020. [HTML]
23. Thirunavukkarasu M, Sawle Y, Lala H. A comprehensive review on optimization of hybrid renewable energy systems using various optimization techniques. Renewable and Sustainable Energy Reviews. 2023 Apr 1;176:113192. [HTML]
24. Mostafa MH, Aleem SH, Ali SG, Ali ZM, Abdelaziz AY. Techno-economic assessment of energy storage systems using annualized life cycle cost of storage (LCCOS) and levelized cost of energy (LCOE) metrics. Journal of Energy Storage. 2020 Jun 1;29:101345. [HTML]
25. Song K, Wang X, Li F, Sorrentino M et al. Pontryagin's minimum principle-based real-time energy management strategy for fuel cell hybrid electric vehicle considering both fuel economy and power source …. Energy. 2020. [HTML]
26. Lin X, Zamora R. Controls of hybrid energy storage systems in microgrids: Critical review, case study and future trends. Journal of Energy Storage. 2022. researchgate.net
27. Villarroel-Schneider J, Balderrama S, Sánchez C, Cardozo E, Malmquist A, Martin A. Open-source model applied for techno-economic optimization of a hybrid solar PV biogas-based polygeneration plant: The case of a dairy farmers' association in central Bolivia. Energy Conversion and Management. 2023 Sep 1;291:117223. sciencedirect.com
28. López-Castrillón W, Sepúlveda HH, Mattar C. Off-grid hybrid electrical generation systems in remote communities: Trends and characteristics in sustainability solutions. Sustainability. 2021. mdpi.com

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