Hybrid Renewable Energy Systems: Opportunities and Challenges in Sub-Saharan Africa

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Abstract

Renewable energy is currently the direction in which the world is headed due to its sustainable, inexhaustible, and pollution free nature. It is gradually replacing conventional means of generating energy supply such as the use of fossil fuels. The appeal of renewable energy comes in its unique application in areas such as rural (off-grid systems), distributed power generation, micro-grid systems, electricity generation, space and water heating, more efficient transportation systems, space and satellite systems, and improved electronics and appliances. The fact that most renewable energy sources are abundantly available and environmental-friendly proposes it to be the solution to the world's energy supply problems. This paper, therefore, provides a short review of hybrid renewable energy system (HRES) with a focus on the opportunities, challenges, and future directions as it relates to sub-Saharan Africa. It highlights current research on hybrid energy systems and the hybridization techniques, standard for HRES optimizations, opportunities, challenges, future directions, applications, off-grid, and micro-grid systems.

Keywords
Renewable energy, energy consumption, energy demand, hybrid energy systems, micro-grids.

1. Introduction

There is a growing demand for energy supply, especially since the advent of the post-modern era defined by the necessity of both the technological and industrial sector in all of humanity's endeavors. According to the International Energy Agency (IEA), the total primary energy supply (TPES) was 1.575 x 10^{17} Watt-hours or 18 Terawatt-years in 2013 (Liao, Cai, Yang, & Wei, 2016). Given this colossal supply of energy, only about 69% of this energy was consumed (Stephenson, 2018). This is attributed to the processes required in refining and transporting the energy especially when generated by conventional methods such as fossil fuels, thereby leading to an even greater demand for energy. Furthermore, fossil fuels, as of 2016, constituted about 80% of the world energy supply (Verdolini, Vona, & Popp, 2018). This shows that the world's current dependence on these rapid depleting resources is high. Hence, the need for the paradigm shift to alternative, more sustainable, reliable and environmental-friendly source of energy couldn't be more emphasized as fossil fuels would not be able to meet the continuously increasing energy demand due to its depleting nature.

Renewable energy is distinguished as the most efficient way to meet this growing demand of energy. This is seen in the fact that over the period from 2000 - 2012, renewable energy had the fastest growth than at any other time in history as the demand for other sources of energy such as nuclear decreased due to nuclear disasters (Dudley & Dale, 2012; Goldemberg, Johansson, & Anderson, 2004). Renewable energy is going to play a key role in futuristic technologies due to its adaptation with the existing technologies and its part in their improvement. Examples of this include more recent hand-held electronics, advancements in electric cars and rocket science using solar energy as a power source. Renewable energy technologies include a wide range of energy resources from solar (Photovoltaic systems and Concentrated Solar Power) to wind power, hydro, biomass, geothermal, oceanic waves and tides.

Renewable energy used as stand-alone power supply system has a low efficiency rate due to the poor conversion efficiency from the energy resource to electrical energy. An example of this is in the solar PV systems which use solar panels with a conversion efficiency of about 20%. Furthermore, most of the renewable energy technology resources though inexhaustible, occur intermittently and unpredictably implying there is no constant supply of the energy resource thereby leading to a poor system performance of the applied technologies. This most times lead to the RE technologies being coupled with the already existing conventional energy supply as a supplement or a backup instead of playing the main role of energy supply. A more efficient way of significantly improving the system performance of RE technologies would be by combining two or more of such power generation technologies together with a storage system in place. This process is referred to as hybridization of renewable energy systems.

2. Hybridization Techniques in Electrical Energy Systems

Hybrid energy systems consist of two or more energy systems combined to improve the overall system efficiency and energy output as well as provide greater balance in energy supply which most times may include a storage facility (Bartolucci, Cordiner, Mulone, Rocco, & Rossi, 2018; Chen et al., 2018). The hybrid energy systems we would be looking at combines two or more renewable energy resources. The HRES may have the two or more RE sources as a strictly renewable system or may also be coupled with a conventional energy source such as a diesel or petrol generator as the power supply system to satisfy the demand of that area. An example of the latter is a PV (Photovoltaic)-Wind diesel generator combined with battery storage HRES as shown in Figure 1 (Ferrari, Bianchini, Galli, Ferrara, & Carnevale, 2018; Gökçek, 2018; Roumila, Rekioua, & Rekioua, 2017).

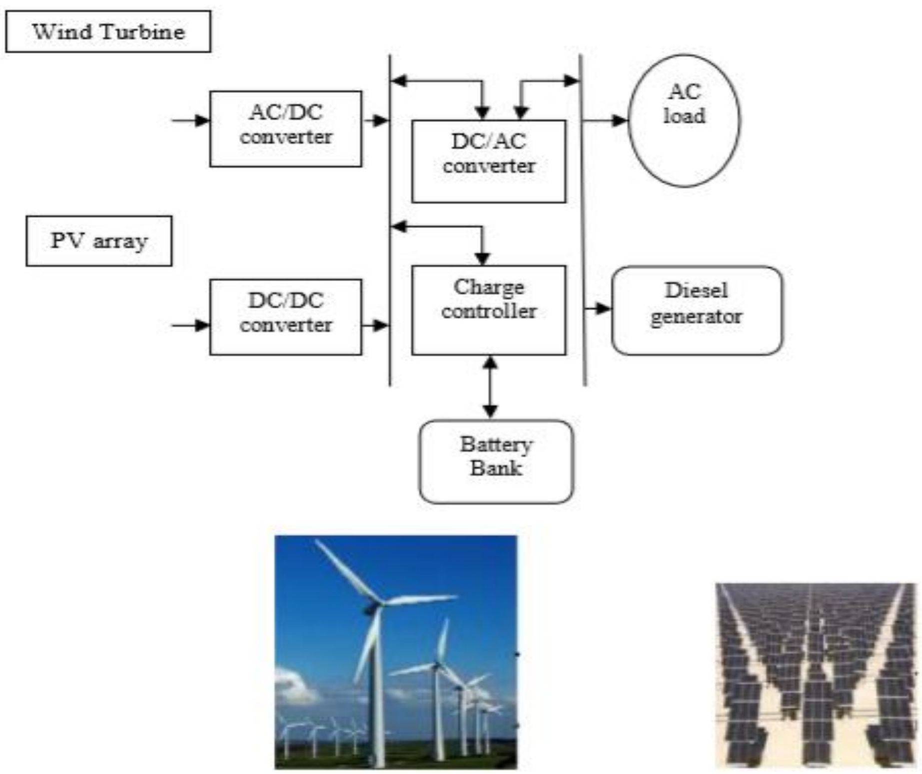

Figure 1. PV/wind/battery/diesel generator HRES (Negi & Mathew, 2014)

To achieve the most efficient HRES, it is important to have an unambiguous and standardized framework to know the most efficient resource combination and the best methodology for power generation especially in off grid systems. The following are the necessary steps in the framework when hybridizing energy resources (Negi & Mathew, 2014).

2.1. Energy Demand Assessment

This implies carrying out load analysis and calculations to accurately estimate the load demand of the area or consumer of the energy. It will also include surveys and interviews thereby allowing accurate load forecasting. This will allow an efficient HRES to be designed to satisfy the energy demand.

2.2. Energy Resource Assessment

This entails the analysis of the geographical area surrounding the energy demand. It is studying the natural resources and their available amounts where the HRES is to be set up to for design considerations of the system. It involves the use of available meteorological data to calculate the potential available in these resources e.g. solar, wind, biomass and other available resources. Limitations and constraints include: accessibility, remoteness, cost, environmental factors, working conditions etc. After taking these factors into consideration, the most suited HRES is designed to meet the required energy demand as efficiently as possible.

3. Energy Resource Assessment

Assessments based on the system life-cycle, cost and power reliability must be carried out to determine the optimal combination of the HRES required to meet the energy demand (Negi & Mathew, 2014).

3.1. System Life-Cycle

This refers to the order of stages that are worked through during the development of the required hybrid renewable energy system from the planning to the installation and maintenance of the system.

3.2 System Cost Analysis

There are various economic factors when dealing with the HRES cost analysis; some of which include the life-cycle cost (Valente & de Almeida, 1998), net present cost and the levelized energy cost (Agbossou, Kolhe, Hamelin, & Bose, 2004). The levelized energy cost refers to the ratio of the total annualized cost of the system to the annual electricity delivered by the system (Negi & Mathew, 2014). The life of the system is considered by the life span of the conversion component such as PV module (Dufo-Lopez & Bernal-Agustín, 2005) or wind turbine. The net present cost refers to the aggregate present value which entails both the initial cost of system's component, maintenance cost and cost of replacement (Negi & Mathew, 2014).

3.3 Power Reliability Analysis

There are several ways to calculate the reliability of HRES as this is an essential step in HRES design process. This includes the loss of power supply probability (LPSP) and loss of load hours (LOLH). HRES must satisfy energy demand in the most cost effective and reliable way.

4. Opportunities of Hybrid Renewable Energy Systems

Due to the current limitations and problems faced by the existing energy supply in terms of coverage, power generation, pollution, poor power supply, and other application such as water heating, improved electronics, the following opportunities have been created for HRES.

4.1 Off-grid and Micro-grid Systems

This is one of the most appealing features of HRES; its application in rural and remote locations. Due to environmental factors, accessibility and coverage limitation of the existing on-grid network, electrical energy supply is not able to reach a significant percentage of the world's population leaving them isolated from the rest of the technologically advanced world and without essential facilities for growth and advancements. HRES can be used as a stand-alone power supply to these areas to give them the platform and access to utilities and facilities which they can use to grow and develop. Furthermore, HRES applied in micro and mini-grids have opportunities in industrial and research and development sectors. Since such sectors require their own network of power supply which includes several energy sources. HRES could play a very important role due to the large amounts of power required to power the facilities and carry out processes.

4.2 Economic Opportunities

Nigeria for instance spends an estimated cost of $14 billion on power generation using petroleum products [11]. Delving into alternative energy and developing such systems as HRES for off-grid and mini-grids solutions to support the grid would save Nigerian homes and businesses a cumulative of $4.4 billion per annum. This contributes immensely to the nation's GDP also creating an incredible market opportunity for companies to invest into HRES due to the high demand for it. Richard Branson (founder of Virgin Group) valued this market opportunity in Nigerian off grid power at $9.2 billion per annum (BOYSE, CAUSEVIC, DUWE, ORTHOFER, & CULLINEN, 2014). This indicates the tremendous economic benefit to both the nation and investors investing in HRES.

4.3 Energy Security

Energy today has become one of the most important diving forces of any nation's economy, functionality and stability. As such, any threat to the supply of energy is a threat to the economy, functionality and stability of that nation. Energy security simply refers to the redundancy and guaranteeing of energy supply in the case of any failure and/or emergency. HRES can provide energy security by diversifying the alternatives of energy supply and thereby significantly reduce dependency on conventional means of energy sources. This also significantly reduces the dependence of any developing nation on developed nations for energy resources which may vary due to geopolitical reasons. HRES can be designed to supply several isolated grids across the nation to back up and support the main grid,

4.4 Climate Change Mitigation

There are great opportunities for HRES in climate change mitigation as this is currently one of the strongest driving forces in the demand for RE technologies due to its pollution free nature. Since the 2016 Paris Agreement, severe actions have been taken to combat climate change. This has led to the growing interest by nations around the world in alternative energy. This has created a large opportunity for HRES to be used as the alternative more efficient means of RE power supply.

5. Challenges of Hybrid Renewable Energy Systems

With the growing demand of HRES come a lot of challenges to the implementation of such systems. This section highlights some of the main challenges to the development and implementation of HRES.

5.1 Policy, Institutions and Regulations

The monopoly of the current energy industry and infrastructure by the major key players has led to a highly centralized system that is unreceptive to newer technologies that are causing an unfavorable shift in the market. Countries today still have their regulations and policies designed around these near-monopoly energy providers. These policies are designed to protect these prevalent and centralized energy generation, transmission and distribution provides thereby forestalling any headway by RE technologies. In the USA, may of the small-scale RE project proposals have been declined due to the scales required by regulations (Markard & Truffer, 2006). There needs to be an amendment of the existing laws and regulations to allow the wide scale introduction of RE technologies especially HRES for the integration with the electric power system.

5.2 Socio-Cultural Challenges

Challenges may stem up from the inadequate attention to cultural and social concerns about HRES advancements. An example of this in Nigeria is with the conventional means of energy supply using oil pipelines in the South-South region. The detrimental effects of this pipeline in that region includes oil spillage in the riverine areas thereby polluting the rivers and damaging aquatic life. This not only affects the ecosystem negatively but also the livelihood of the indigenous people of that area. The exploratory and extraction process of this energy and economic resource also leads to severe environmental degradation and pollution which has adverse effect on the agriculture and health of the indigenous people. This coupled with the fact that the indigenes are not financially compensated has led to the rise of insurgents known as the "Niger Delta militants" that continuously vandalize and burn such oil pipelines thereby costing the nation a lot in revenue and resources.

Hence, for advancements in HRES that might require a vast amount of land and other resources that might disrupt the agriculture and livelihood of the indigenes of that location as well as cause a reduction in potential land areas for urban development (Hynes & Hanley, 2006), considerations, compensations, agreements and systems for the affected and displaced indigenes need to be mad.

5.3 Financial and Economic Challenges

Because of the high initial investment cost of HRES, it discourages a lot of potential investors from going into it especially in developing nations. Many developing nations around the world also don't consider HRES due to the large financial risk it presents and uncertainties in future electricity prices (Sen & Ganguly, 2017). These uncertainties lead to high financing costs in research, development and deployment (Mustapa, Leong Yow, & Hashim, 2010). Oftentimes, the initial cost for an efficient equipment is significantly higher than the standard alternative and the payback period or economic return may be inadequate (Mustapa et al., 2010).

6. Future Directions of Hybrid Renewable Energy Systems

There is a lot of potential in RE technologies especially hybrid renewable energy systems. With more research advances being made and breakthroughs in technology, the possibilities of HRES are endless. This section highlights some of the future possibilities and applications of hybrid renewable energy systems.

6.1 Smart Grids and Smart Cities

A smart grid refers to an electrical energy supplied network that uses digital communications technology, to detect and react to local changes in operation. It is basically an advanced grid network that employs the use of smart meters, smart appliances, RE resources and energy efficient resources. The application of HRES in smart grids would lead to its most efficient application as smart grids use digital technologies to optimize the energy generation, transmission and distribution. Smart grids involve processes like automated load balancing/adjustments and has such a high flexibility that allows greater penetration of highly fluctuating RE resources such as wind and solar power even without combining them with an energy storage facility. HRES in smart grids also allow the safe, secure and reliable aggregation of distributed and RE resources. Smart cities are highly dependent on smart grids to ensure consistent energy supply for their functions which is significantly improved by the application of HRES.

6.2 Aviation

HRES has great applications in aviation systems and is proposed to be the future of aviation. An example of this is the combination of a solar-wind powered source with the jet fueled engines of an airplane to power the plane's avionics. The solar powered experimental aircraft project known as "solar impulse" showed the reliability of solar power as an energy source. The solar impulse aircraft made a round trip around the earth powered by solar energy only. Imagine the possibility of HRES here as solar energy alone was enough to accomplish that feat. Imagine what a solar-wind hybrid system with energy storage would be able to accomplish. More advancements are being made in this field by not only using a solar-wind hybrid combined with the jet fueled engines but by also using the solar energy to create solar fuel to power the engines as well. Solar fuel is created by using solar energy to separate the hydrogen from oxygen in water.

6.3 Electric Vehicles

With the direction the world is headed and its attempt to combat climate change by significantly reducing carbon foot print. There has been the advent of electric cars which are gradually replacing conventional gasoline-powered cars. With electrically powered cars come the possibility of using RE technologies such as HRES to power such cars. Current electric vehicles have batteries which require frequent charging at charging spots that are on-grid and within a certain coverage. The application HRES completely eliminates this coverage limitations as the vehicles would be completely autonomous and would not be restricted to being operated within a certain region due to charging limitations. The vehicles would be able to completely function of the grid as they would rely on universal renewable resources to be powered. An example of this is a solar PV-wind powered electric vehicle with energy storage. Application of HRES to electric vehicles improves the overall system performance. Developed nations like Germany for instance are setting in place regulations to have electric vehicles taking the upper hand in sales by 2030 with an estimated sale per year of 5 million EVs.

7. Conclusion

This paper gives an overview of hybrid renewable energy systems (HRES). Several aspects such as hybrid energy systems and hybridization techniques, standard for HRES optimizations, opportunities, challenges and future directions are distinctly reviewed. This paper is to facilitate more research advancements in the topic by emphasizing the importance and demand for hybrid renewable energy systems as an alternative, reliable, sustainable and more efficient means to generate energy, meet the world's energy demand and be the solution to the world's energy crisis.

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Biographies

Ayooluwa A. Ajiboye is currently a senior undergraduate student of the Electrical and Electronics Engineering program at Covenant University, Ota, Nigeria. His research interests focus on four main fields: Applications of Renewable Energy, Mechatronics, Power Electronics and Power Systems. He has a great desire to improve upon the world's energy system which informs his research interests; to see the world employ more sustainable and environmentally friendly means of energy to run its systems. He is part of the team working on the Implementation of Hybrid Renewable Energy Systems in Sub Saharan Africa. He has had experiencing working with a company that specializes in the design and production of inverters as an alternative energy supply employed in solar and off grid systems. Also, he has training on the operations of the Nigerian power grid/power systems. These experiences align with and further his goal of sustainable energy application.

Segun I. Popoola completed his Master of Engineering (MEng) degree in Information and Communication Engineering at the Department of Electrical and Information Engineering, Covenant University, Ota, Nigeria with a Distinction in June, 2018. He was the Overall Best Graduating Masters Student in Covenant University (2017/2018). Segun graduated from Ladoke Akintola University of Technology, Ogbomoso, Nigeria in 2014 with a BTech (First Class) degree in Electronic and Electrical Engineering. He was awarded the Best Graduating Student in the Department of Electronic and Electrical Engineering by the Faculty of Engineering and Technology in conjunction with the Nigerian Society of Engineers (NSE). He has authored and co-authored more than fifty (50) academic papers published in international peer-reviewed journals and conference proceedings. His research interests are, but not limited to: wireless communications, radio propagation modelling, Internet of Things (IoT), machine learning, and data analytics.

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