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Review on Renewable Hybrid Energy and Power Project Design for Sustainable Development

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***Abstract*-** **Micro-grid, an innovative area in the power sector, has huge potential to diminish the cause of blackouts, power deficiencies and its independence help to deliver uninterruptable power to the customers. Micro-grids can offer a great choice for integrating localized renewable energy generation. Hybridizing renewable energy sources grant a realistic form of power production. Renewable and hybrid energy systems (HESs) are expanding due to environmental concerns of climate change, air pollution and depleting fossil fuels. Moreover, HESs can be cost-effective in comparison with conventional power plants. This paper reviews current methods for designing optimal HESs. The survey shows these systems are often developed on a medium scale in remote areas and standalone, but there is a global growing interest for larger scale deployments that are grid connected. Examples of hybrid energy systems are PV-Wind-Battery and PV-Diesel Battery. PV and wind energy sources are the most widely adopted. Diesel and batteries are often used but hydrogen is increasing as a clean energy carrier. The design of an efficient HES is challenging because HES models are non-linear, nonconvex, and composed of mixed-type variables which cannot be solved by traditional optimization methods. Alternatively, two types of approaches are typically used for designing optimal HESs: simulation-based optimization and metaheuristic optimization methods. Simulation-based optimization methods are limited in view of human intervention which makes them tedious, time consuming, and error-prone. Metaheuristics are more efficient because they can handle automatically a range of complexities. In particular, multi-objective optimization (MOO) metaheuristics are the most appropriate for optimal HES because HES models involves multiple objectives at the same time such as cost, performance, supply / demand management, grid limitations, and so forth. This paper shows that the energy research community has not fully utilized state-of-the-art MOO metaheuristics. More recent MOO metaheuristics could be used such as robust optimization and interactive optimization.**

Keywords: Hybrid Model; Micro-grids; Prediction; Renewable energy; Sustainability

1.0 INTRODUCTION

An eternally growing demand for non-renewable energy resources like coal, oil, and natural gas is driving society towards the study, research, and development of renewable energy sources. The renewable energy sources are favored for being environmentally friendly. Renewable energy-based distributed generators play a leading task in electricity generation, with the aim of the cleaner energy solution. The combination of renewable energy sources to form a hybrid system consists of two or more renewable energy sources is an incredible selection for distributed energy production. The power ranges of renewable energy production are minimum that, these renewable energy generation technologies are sited near the load or connected to the utility grid [Naik, et al., 2014]. The rural areas are far-off from the central grid network and the connection is possible only through a weak transmission line. The concept of hybrid power system production is considered as a valuable solution to convene our energy demands [Meziane, et al, 2013]. The increasing energy demands, and increase in producing and carrying capability in the dynamic plants are the reasons to move from the conventional grid to a smart grid. Micro-Grid can be referred to as a subsystem of Smart Grid that is monitored and controlled through advanced technologies. The smart grid is a comparatively novel move for the forthcoming power system that integrates electrical energy and communication on the power system network which gives the digital information on the real-time network operation for the consumers and operator. Additionally, advanced control methods, digital sensing, and metering, advanced grid devices are a few of the major technologies involved in the execution of the smart grid. Optimization of performance, system reliability on hybridization, and operational effectiveness are some of the key characteristics that concerned in smart grid
systems. Therefore, the Micro / Smart grid technology broadens power knowledge and as well it involves interdisciplinary research areas such as automation, communication, sensor, monitor, and control.

2.0 RENEWABLE ENERGY SYSTEMS MODELLINGS

This sections describes some of the existing models for commonly used RES such as photovoltaic (PV), wind, Fuel-Cells

2.1. Modeling of photovoltaic systems

Understanding factors that affect the performance of PV modules is of great importance in order to achieve a precise anticipation of the PV module performance under variable climatic conditions. Many researchers worked in this direction. Overstraeten and Mertens (Overstraeten and Mertens, 1986) developed the fundamental model of PV cells. Borowy and Salameh (Borowy and Salameh, 1996) introduced a simplified model that calculates the maximum power output for a PV module based on the solar radiation and the ambient temperature. Jones and Underwood (Jones

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and Underwood, 2002) proposed a more complete model by calculating the PV power output efficiency model. Kerr and Cuevas (Kerr and Cuevas, 2003) introduced a model for calculating current–voltage (I–V) of PV modules by measuring pen-circuit voltage under variable light intensity. Nishioka et al. (Nishioka et al., 2003)studied the temperature impact on the PV system annual output; it appears that the annual energy output of the PV system increases by about 1% for every 0.1%/C° temperature coefficient improvement. Stamenic et al. (Stamenic et al., 2004) examined low irradiance efficiency of PV modules installed on buildings. Zhou et al. (Zhou et al., 2007) introduced a "simple" simulation model for PV array performance predictions under operating conditions, with limited data available from PV module manufacturers. Mondol et al. (Mondol et al., 2005) developed a simulator for building integrated photovoltaic; the monthly average error between measured and predicted PV output was estimated to be 6.79%.

2.2. Modeling of wind systems

The modeling of wind energy systems includes wind turbine specifications and generator modeling. One of the simplest models to simulate the power output of a wind turbine was proposed by Ghali et al (Ghali et al, 1997); they used a probabilistic approach to simulate a hybrid PV-wind-battery energy system. Borowy and Salameh (Borowy and Salameh, 1994 and 1996) used a statistical method for calculating the power

output from a wind turbine; they assumed the wind speed distribution to be a Weibull distribution. Karaki et al. (Karaki et al., 1999) proposed a probabilistic model to simulate an autonomous wind energy conversion system composed of several turbines connected to a battery. Lu et al. Nehrir et al. (Nehrir et al, 2000) developed an algorithm that simulates the power output from the wind turbine based on wind average speed, the electrical load, and the power curve. The wind turbine power curves do not always represent wind turbine power output with exactitude because they neglect instantaneous wind speed variations, and therefore, undermine the wind turbine performance (Muljadi and Butterfield¸ 2001). Therefore, Zamani and Riahy (Zamani and Riahy, 2008)introduced a new way for calculating the wind turbine output power by taking into consideration the wind speed variations.

2.3. Modeling of Hydrogen Fuel Cells

The hydrogen fits well hybrid RESs because of several reasons (Naterer, 2008). It is decentralized and intermittent supply in similar fashion as the wind and PV RESs. Also, It can become economically more viable the predominant steam-methane reforming technology if merged properly with other RESs. In addition, the hydrogen can be reused as backup power generator, for regenerating electricity during peak hours, or used as is for transportation or other purposes. Once the hydrogen is generated, it can be reconverted to electricity using fuel-cell technology. A fuel-cell is an electrochemical mechanism to generate electrical current (DC) from hydrogen and oxygen. Initially, Vanhanen et al. (Vanhanen et al., 1994) proposed a simulation PV-hydrogen system that generates hydrogen for PV panels, and then it reconverts it back to electricity. Then Amphlett et al. (Amphlett et al., 1994), Kim et al. (Kim et al., 1995), and Lee et al. (Lee et al., 1998) worked on modeling of proton exchange membrane fuel-cell stack. Mann et al. and Fowler et al. (Mann et al., 2000; Fowler et al., 2002) continued to work on more precise models such as the degradation effect on the fuel-cell performance. Later, Cheddie and Munroe (Cheddie and Munroe, 2005) presented a review of on proton exchange membrane fuel cell modeling. In this review, they categorize the fuel-cell models as analytical, semi-empirical, mechanistic. More recently, Mann et al. (Mann et al., 2006 and 2007) emphasized on activation and concentration polarization. Another aspect regarding hydrogen that needs to be addressed is its storage. The hydrogen storage is even more critical in hybrid energy system because Solar and Wind energy sources are inconsistent. Deshmukh and Boehm (Deshmukh and Boehm, 2008) categorise current available hydrogen storage technologies as compressed hydrogen, liquid hydrogen, metal hydrides, and carbon-based materials (flullerenes, carbon nanotubes, activated carbons). An extensive literature review of PV, wind, and FC models can be found in Ref. (Bañosa, 2011).

3. SIMULATION-BASED OPTIMIZATION OF ENERGY SYSTEM COMPONENTS

Currently, researchers working on RESs are mainly focusing on solar and wind energy sources. The photovoltaic array area, the specificities of wind turbines, and the storage capacity have an important role in operation of hybrid PV-wind energy systems, while satisfying load (Wu and Liu). The most common renewable standalone hybrid energy systems are: PV-Wind-Battery, PV-Diesel-Battery, and HydroelectricPV-Wind-Battery. None of these are completely benign renewable energy systems because of the battery component. The solar and wind systems are intermittent sources of energy which require storage like a battery to form a PV-wind-battery system (Bernal-Agustín J., Dufo-López, 2009), or a backup energy source such as diesel to form PV-wind-diesel systems (Bernal-Agustín J., Dufo-López, 2009b). In both cases, the hybrid energy system is not completely renewable. The most common RES-based systems are not completely sufficient by themselves because of the intermittence of the wind and solar sources. Hydrogen is a cleaner alternative for energy storage, and it can be used for regenerating electricity by using fuel-cells.

The hybrid energy system designs are mainly dependent on the performance of their respective components. In order to forecast the system's performance, these components should be modeled and simulated. Then their combination could be evaluated to determine if it satisfies the demand load. If the power output estimation from these individual components is accurate enough, their combination can deliver power at the lowest cost. Most of the simulation papers for hybrid energy systems use the HOMER (Hybrid Optimization Model for Electric Renewables) tool (HOMER, 2010), developed by NREL (National Renewable Energy Laboratory, USA) because of its capabilities and flexibility. It can optimize a wide range of energy components: photovoltaic generator, batteries, wind turbines, hydraulic

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turbines, AC generators, fuel cells, electrolyzers, hydrogen tanks, AC–DC bidirectional converters, and boilers. The loads can be different types: AC, DC, and/or hydrogen or thermal loads. In addition, the tool is available free of charge.

3.1. Simulation-based optimization of photovoltaic systems

Shaahid and Elhadidy (Shaahid and Elhadidy, 2007) used the HOMER tool for cost optimization of a PV–Diesel–Battery system to supply a shopping center in a desert area. The hybrid energy system reduced the diesel consumption and pollution by 27%. Shaahid and El-Amin (Shaahid and El-Amin, 2009) used HOMER for finding an optimal design of a PV–Diesel–Battery hybrid energy system, rather than diesel-only, for supplying a remote village in Saudi Arabia. The study examined the effect of PV/battery penetration on the cost of electricity, the unmet load, the electricity excess generation, percentage of fuel savings, and reduction in carbon emissions. The results showed that the optimal combination is the PV-Diesel-Battery rather than Diesel-only or PV-Diesel. The percentage of fuel savings by using a hybrid PV–diesel–battery energy system (2.5 MW PV, 4.5 MW diesel system, 1 h storage, 27% PV penetration) is 27% less than using diesel only. In addition, the carbon emissions decrease by 24% (1,005 tons/year) as compared to the dieselonly scenario. Li et al. (Li et al., 2008) used simulation methods for the development of a standalone PV system. Due to the intermittent nature of the solar energy, they considered batteries and/or fuel cells (FC) for energy storage. The hybrid PV-battery-FC energy system appeared to be the cheapest, most efficient, and least demanding in terms of PV module numbers as compared to either single storage system. Wies et al. (Wies et al., 2005) simulated, with Simulink and HOMER, a real hybrid PV–Diesel–Battery energy system located in Alaska. They compared it with a system with only a diesel generator, and another Diesel–Battery system to supply energy for the same load. The results indicated that the system with only a diesel generator had a lower installation cost, but higher operation and maintenance costs.

3.2. Simulation-based optimization of wind systems

Himri et al. (Himri et al., 2008)used the HOMER software tool for the optimization of energy production, life cycle cost, and the greenhouse gas emissions of a hybrid energy system. The hybrid wind-diesel energy system is a grid-connected power plant supplying energy to a remote village. The results show that the wind– diesel hybrid system becomes feasible when the wind speed reaches 5.48 m/s and the fuel price is 0.162$/L or more. The maximum annual capacity shortage did not impact in any way on the system optimization. Lu et al. (Lu et al., 2002) used probabilistic models to select the optimal (maximum power output) turbine characteristics, depending on the yearly wind properties. They found that hub height is an important factor. At 37 m, the wind turbine can function for 6,820 hours (77.85%) a year and generate 32,400 KWh with a capacity factor of 0.387 for Waglan Island. 3.3. Simulation-based optimization of fuel-cell systems

The hydrogen FCs fit well with hybrid energy systems for several reasons (Naterer, 2008). First, FCs provide a decentralized supply in a similar fashion to wind and solar RESs. Second, hydrogen can be generated during off-peak periods where electricity prices are low. Third, the hydrogen FC can be reused as a backup

power source; it can be used for example for regenerating electricity during peak hours. The FC mechanism generates Direct Current (DC) from hydrogen and oxygen. As mentioned previously, Li et al. (Li et al., 2008) examined on a combination of FCs with PV-battery systems. Deshmukh and Boehm investigated variant forms of hydrogen storage technologies that are currently available (Deshmukh and Boehm, 2008): compressed hydrogen, liquid hydrogen, metal hydrides, and carbon-based materials (fluorescence, carbon nanotubes, activated carbons).

3.4. Simulation-based optimization of PV-wind systems

McGowan and Manwell (McGowan and Manwell, 1999) discussed PV–Wind–Diesel–Batteries hybrid energy systems in different locations in the world using the HYBRID2 tool (Hybrid2, 2010). They concluded that hybrid energy-related research should further examine the reliability of components and systems, improve the documentation and monitoring of system performance, and reduce the cost of the renewable energy components. Furthermore, they designed PV–Wind–Diesel–Battery systems for different applications in South America (McGowan, 1996). They found by comparing HYBRID2 and SOMES tools that they provide similar results, and they can be used to design and size such systems. However, there is no universal tool yet, and different types of problems need to be solved through the use of different approaches and tools. Karaki et al. (Karaki, 1999) examine simulation algorithms for PV–Wind–Battery systems. They report on economics of hybrid PV–Wind–Battery energy systems. However, the battery capacity is limited, depending on the required charging/discharging cycle time. Elhadidy (Elhadidy, 2002; Elhadidy and Shaahid, 2000) studied the performance of possible variances of PV-wind-diesel systems. It has been found that PV panels are economically not yet viable for desert areas in Saudi Arabia. Nfah et al. (Nfah et al., 2007) proposed a design for a PV–Wind–Diesel–Battery system located in a remote area in the north of Cameroon. They demonstrated that the hybrid energy system can generate 70 – 2,585 kWh/yr rather than extending the grid. Diaf et al. (Diaf et al., 2008) studied the optimization of economic and technical performance of a standalone hybrid PV-wind-battery energy system on Corsica Island. They compared the optimum dimensions of the system in five sites on the island. The results showed the hybrid energy system offers a better performance than a single source system. The PV system was not affected by changing sites; however, the wind system dropped from 40% power generation to 20%, depending on site location. Dalton et al. (Dalton et al., 2008) worked on the design optimization of a standalone renewable energy PV-Wind-battery-Diesel system, using HOMER and HYBRIDS tools, for a large hotel (4,100 beds) located in a subtropical coastal area in Australia. More specifically, they compared diesel

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generator-only, PV-WindBattery, and PV-Wind-Battery-Diesel hybrid technologies. Three objectives were considered: the Net Present Cost (NPC), renewable fraction (RF), and payback time. The result showed that it is possible to build a completely RES that meets the demand load. However, a hybrid diesel-Wind-battery configuration provides the lowest NPC result with a resultant RF of 76%. The NPC is reduced by 50%, and the greenhouse gas emissions by 65%. Mondal and Denich (Mondal and Denich, 2010) studied the potential of PV, Wind, Biomass, and Hydro energy sources in Bangladesh. The results showed that PV grid-connected sources have the highest potential for the country. Prodromidis and Coutelieris (Prodromidis and Coutelieris, 2010) examined an existing RES installed in Leicestershire, UK. The system is a standalone PV-Wind-FC. By using the HOMER tool, it was determined how to optimize the use of the system and the cost impact of connecting the RES system to the grid. Results showed that in the long term, the connection to the grid will be costly. Balamurugan et al. (Balamurugan et al., 2009) used the HOMER tool for designing an HES composed of biomass-PV-Wind-battery in a remote area. The objective was a combined maximization of the supply of energy to the loads and minimization of the supply of energy from the sources. A sensitivity analysis was performed for the load, wind speed, and solar radiation. The proposed system satisfied the load demand, nonlinear seasonal variations, and equipment constraints of three different typical villages in India. Figure 1 is an example of a hybrid PV-Wind modeling taken from Ref. (Zhou et al., 2010).

3.5. Simulation-based optimization of solar-wind-fuel-cell systems

Dufo-López et al. (Dufo-López et al., 2009) worked firstly (case A) on the design and economic analysis of hybrid PV-Wind energy systems. In addition (case B), they considered the use of these systems for generating hydrogen when the amount of electricity is not needed by the demand load. Finally (case C), the reuse of hydrogen was considered for regenerating back electricity when the demand is high. The results (case A) showed that hybrid PV-Wind energy systems match well and they are more economical than the use of a unique energy source. For case B, the generation of hydrogen for selling purposes appeared to be economically viable only for locations having a high average wind speed (> 4.66 m/s). For case C, the use of hydrogen for regenerating electricity by fuel cells was not economically viable based on the electricity prices in Spain. The authors attribute this to a low energetic efficiency rate of the electricity-hydrogen-electricity process. However, if the electricity prices were higher or the energetic efficiency rate improved, the model would become viable. Zervas et al. (Zervas et al., 2007) developed a framework for HES that used hydrogen for energy storage. Thus, they tested the framework with a PV-FC system connected to a grid in Greece. The proposed tool is especially useful for HES that incorporate hydrogen systems. Figure 2 is an example of a PV-FC (hydrogen) model taken from ref. (Hwang et al., 2009).

4.0 KEY DRIVERS FOR DEVELOPING HYBRID RENEWABLE ENERGY SYSTEMS

4.1 Economic consideration

With renewable energy sources and its automation technologies, micro-grids get benefitted economically and environmentally. Power generating units with distributed generations helps to sustain the economic processes in the main utility to organize local demand for the promotion of energy efficiency and clean electricity [3]. Energy efficiency is extremely significant for the hybrid renewable system and it should be stimulated by fixing suitable prices and this is mainly important wherever the price for energy is growing. The essential cost-effective criteria available for the development of renewable hybrid systems are Net Present Cost (NPC), Cost of Energy (CoE), Economic Rate of Return (ERR). The Net Present Cost (NPC) is called a total gain of all costs which includes assets investment, non-fuel maneuver, and management costs, costs invested for energy supply, alternate tool costs, and some other costs for example fees payment in a legal manner. In order to achieve the most approvable financial option for emerging hybrid renewable energy design, the minimum Net Present Cost should be considered as a choice. The computational cost for the production of electric power at the connection point of a load or utility grid is stated as the Cost of Energy (CoE). For performance optimization, the energy costs involved with the capital cost, product cost like fuel, concession price, in addition to the costs of a continuous process, and safeguarding. The Economic Rate of Return (ERR) also called as Internal Rate of return utilizes capital expenditure for determining and evaluating the effectiveness of investments [Amphlett JC et al].

4.2 Shortage of electric power supply

At Present, scarcity of electrical energy has been a prevalent occurrence in many emerging countries. India is also facing an energy disaster because of its major addiction to coal, oil, and natural gas imports to convene sharply increasing the energy desires of the country. And so, for the last decade, the Indian power sector has taken some considerable evolution. With that, the Government of India has supported several initiatives to enhance the power sector of India. The insufficient power production can result in repeated power outage conditions and rationing of energy supply. Restricted access to energy can convey about the straining of living. This trouble is not in an actual sense due to lack of energy resources but can be recognized to some other aspects like incomprehensive scheduling and management of resources, economic challenges, poor energy policies, and constraints in energy financing and execution models. The challenges of energy shortage have been set on in many rural and remote communities which include urban cities using renewable energy systems. Introducing a smart grid system is a solution which enables the possible renewable resources integration and transfer from dependence on fossil fuels, for maintaining and managing the stability among energy supply and energy demand.

Environmental perception The growth of smart grid technology development at a high speed is because of the wide awareness of policymakers and utilities in minimizing the unfavorable outcome that energy usage has on the environment. A set of micro-grid (Smart grid) uses technology to constrain efficiencies in transmission, distribution, and consumption. Consequently, fewer generating units, fewer transmission, and distribution resources are necessary in order to outfit the rising demand for electrical energy. With the promising hope of wind farmhouse sprawl, landscape maintenance is one of the evident benefits. Since a large amount of power production today consequences in the discharge of greenhouse gas, smart grids play a role in reducing air pollution and struggling against global climate change issues. A smart grid has the potential to hold technological difficulties of combining renewable resources like solar and wind to the grid and providing an additional reduction in greenhouse gas emissions.

4.3 Suitability of System

Srivastava et al., 2015 [5] have carried out a study on the suitability of the system. Rural areas in India amount to concern the total land area of the country and about seventyfive percentage (75%) of the population of the country exist in these areas. The living circumstance here is very unhealthful and people lack here for fundamental facilities like water supply, electricity, roads, education, etc. So as to bring people living wage in these areas in typical and to put off large scale migration from these communities to urban cities we need to build up some sources that can accomplish their fundamental needs amongst them vital classification to be electricity. Moreover, in this case, hybrid renewable energy systems can show to be the most important progressive result of these troubles. The suitability of different techniques in hybrid renewable energy sources was classified by (Srivastava et al., 2015) [5] could found to a solution and the type of region is termed on the basis of geographical outline and location of that particular region. Also, this study reproduces the suitability of various systems on the basis of the geographical features which are reported in Table 1

Table 1: Suitability of different hybrid renewable energy system on the basis of geographical terrain (Srivastava et al., 2015) [5]

Geographical feature	Type of HRES applicable	Recommendations
High Altitude	Biomass-wind-fuel cell, photovoltaic-wind, photovoltaic-biomass	Photovoltaic-biomass
Mountain	Biomass-wind-fuel cell, photovoltaic-wind, photovoltaic-biomass	Photovoltaic-biomass
Plain	Photovoltaic-biomass, hydro wind, solar flower, combined HRES plant, biomass-wind, photovoltaic-wind	Combined HRES plant
Semi-Desert	Wind-fuel cell, wind-photovoltaic, wind-biomass, photovoltaic-biomass, photovoltaic-wind-biomass,	Photovoltaic-Wind Biomass
Desert	Wind-fuel cell, wind-photovoltaic, wind-biomass, photovoltaic-biomass, photovoltaic-wind-biomass,	Photovoltaic-Wind Biomass

4.4 Theft control

In developing countries like India, where people have a slight insight into the grid and higher poverty rate, power theft is quite common. Xue et al., 2014 [6] stated that the rapport among the energy markets with physical energy pattern has been hold by the control of economic transmit under security restrictions. Hence with the growth of the smart grid, power theft can be controlled to a greater extent, thus improving the efficiency of our distribution system. The greater efficiency has been achieved by introducing smarter technologies at the distribution structure which can be able for detecting as well as minimizing the thefts at the consumer premises. Thus grids will offer high quality and reliable electricity supply and there may be fewer blackouts.

4.5 Utilization of energy storage system

Electrical Energy Storage system is the progress of converting electrical energy from a power system into a form which can be stored for converting back to electrical energy whenever it is needed. This technique enables electricity to be produced at times of either low generation cost, low demand, or from alternating energy sources and to be used at times of high generation cost, high demand, or when no other generation resources are availed [7]. Kong et al., 2012 [8] have analyzed the benefits of a storage system for a micro-grid. In a microgrid, the energy storage systems are used to compensate/eliminate power fluctuations. Because of the limited capability of energy storage systems and infinite charge/discharge for compensation can cause overcharge or else over-discharge of the electrical energy storage system. As a result, it is essential to control the storage system with a state of charge to function the micro-grid steadily.

4.5 Optimization Of Energy System Components

Several papers have been published regarding the optimization of hybrid energy sources. However, this study focuses on recent studies published in the last decade. Usually, an optimum combination of hybrid energy sources needs to address several objectives. Among them, the system and the production costs should be minimal, the load demand should be met, and the power should be reliable. Sometimes, HES is optimized by taking all the objectives at the same time. And sometimes, one objective is optimized whereas other objectives are transformed into constraints. Both approaches are described in the next subsections.

Single objective optimization for hybrid energy systems design

Koutroulis et al. (Koutroulis et al., 2006) worked on designing a standalone hybrid PV-wind-battery energy system by focusing on the minimization of a 20-year total system cost. This cost is the sum of the components of capital and the maintenance fees. In addition, the solution is constrained by the load energy requirements that need to be completely covered, i.e., a zero load rejection. A genetic algorithm (GA) was used and it attained the global optimum faster than conventional optimization methods such as dynamic programming and gradient techniques. In addition, the result showed that a standalone hybrid PV-Wind energy system is lower cost than the exclusive usage of one energy source.

Weinstock et Appelbaum (Weinstock et Appelbaum, 2004) used Sequentiel Quadratic Programming for the optimization of solar field design. They divided their system into three sub-problems: energy maximization, minimization of the area field, and maximization of the solar unit area. They found that it is possible to increase the yearly energy by about 20% and a decrease of about 15% of the field area, compared to the current industrial standards in their area.

Ashok (Ashok, 2007) used Non-Linear optimization for the design of a PV-Wind-Micro-Hydro-Dieselbattery system. They have found that a micro-hydro/wind hybrid energy system to be the most optimal combination from the cost perspective. In addition, it is the cleanest combination because of no diesel in the system. The system is tested in India (Western Ghats - Kerala).

Yang et al. (Yang et al., 2009) studied the design of hybrid solar–wind-battery energy systems. It was possible to calculate the system's optimum configurations while minimizing the annualized cost of the system, with respect to the required loss of power supply probability (LPSP). Five decision variables were considered in the optimization process: PV module number, PV module slope angle, wind turbine number, wind turbine installation height, and battery capacity. The results showed that it was possible from GA to attain the global optimum with relative computational simplicity. The proposed hybrid energy system served as a power supply for a telecommunication relay station located in the southeastern coast of China.

Tina et al. (Tina et al., 2006) used a probabilistic approach based on a convolution technique for assessing long-term performance of a hybrid grid-connected PV-wind energy system. The system permitted the evaluation of different economic objectives such as electric contract demand, expected values of annual total cost, annual energy consumption, and others. The results of the analysis were not used only for the index of reliability calculation, but also allowed the documentation of other relationships between system parameters of interest.

Dufo-López and Bernal-Agustín used Genetic Algorithms (GAs) for designing an optimal PV-Dieselbattery system (Dufo-López and Bernal-Agustín, 2005). GAs were used because of mixed type variables: Boolean, integer, discrete. One GA served for selecting the components, while the second served for handling electric dispatch strategy (Cycle Charging or Combined). They integrated the GAs into the HOGA tool. It appeared that the GA algorithm offered more precision than traditional methods because it was possible to get the number of PV panels, as well as their type, and the number of batteries in parallel, as well as their type. Also, HOGA was compared to the HOMER (Hybrid Optimization Model for Electric Renewables) modeling tool [39], which they mentioned to be the best tool available. HOMER can optimize a wide range of energy components: photovoltaic generator, batteries, wind turbines, hydraulic turbines, AC generators, fuel cells, electrolyzers, hydrogen tanks, AC–DC bidirectional converters, and boilers. In addition, the loads can be of different type: AC, DC, and/or hydrogen or thermal loads. In addition, the tool is available free of charge. After the comparison, HOGA appeared to be faster and more precise than HOMER. This performance is attributed to the use of GAs by HOGA. Esfandyar et al. (Esfandyar et al., 2011) worked on the design of PV systems which are connected to storage units (compressed-air-energy-storage and super-capacitors), and also grid connected. They have used the OptQuest (Glover et al., 1999) tool for the design, which incorporates three meta-heuristics Scatter Search, Tabu Search, and Neural Networks. They successfully obtained an optimal mixture of required capacities of the systems.

Kaabeche et al. (Kaabeche et al., 2011) performed a case study on a PV-Wind-Battery system in Algeria. They have used a GA for system optimization. Zhao et al. (Zhao et al., 2009) proposed a GA for designing a wind farm by optimizing the production cost and system reliability. Senjyu et al. (Senjyu et al., 2007) used a GA for the design of a PVWind-battery-diesel system in Japanese islands. The results showed that HES systems reduce the cost by 10% in comparison with diesel generators.

Kaviani et al. (Kaviani et al., 2009) used the Particle Swarm optimizer for the design of a PV-Wind-FC system. They demonstrated the importance of considering outage scenarios in the design. Hakimi et al. (Hakimi et al., 2009) used a PSO algorithm to optimize the design of a wind-FC system in a remote area in Iran. The designed system was sufficient to cover the demand of that area.

A limitation of the previous studies is that all of these tools optimize a single objective. They consider other objectives as constraints or variables. Nevertheless, the design of hybrid energy systems (HESs) is a multi-objective problem, and it should be modeled accordingly. The next section reviews multi-objective optimization methods applied to the design of HES.

4.6 Multi-Objective Optimization for hybrid energy systems design

Dufo-Lopez et al. were the first and only research group to our knowledge that have used multi-objective optimization (MOO) metaheuristic methods for HES design (Dufo-Lopez et al., 2006 and 2008). They developed a tool called HOGA (HOGA, 2010). According to their survey (Bernal-Agustín J. and DufoLópez, 2009), it appears that this is the only tool that uses a MOO meta-heuristic for HESs. It supports, according to the user manual, the following objectives: total cost (Net Present Cost (NPC)) versus CO2 Emissions, or total cost (NPC) versus unmet energy. It can handle various components: photovoltaic generator, batteries, wind turbines, hydraulic turbine, AC generators, fuel cells, electrolyzers, hydrogen tanks, rectifiers, and inverters. The loads can be AC, DC, and/or hydrogen.

First, Dufo-Lopez et al. (Dufo-Lopez et al., 2006) worked on the design of PV–wind–diesel-battery using MOO metaheuristic for the first time. The problem was composed of two objectives: minimization of cost through the useful life of the installation and the pollutant emissions while guaranteeing electrical energy supply at all times. The system generated a Pareto front composed of 50 solutions.

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The designer could choose the most appropriate solution, considering the costs and pollutant emissions, which demonstrate the practicality of using MOO methods. Then, Dufo-López et al. (Dufo-Lopez et al., 2008) used the same algorithm (SPEA) for the same problem by adding more real-world complexity. They used a GA for a control strategy. Also, they added unmet load as a third objective and Hydrogen-based Fuel-Cells as an additional type of storage component. They developed a triple multi-objective design of a standalone PV-Wind-Diesel-Hydrogen-Battery hybrid energy system. The system was located in Zaragoza, Spain. The SPEA algorithm was used for the simultaneous minimization of three objectives: the total net present cost, pollutant emissions (CO2), and the unmet load. The processing resulted in a Pareto front of 35 solutions from which the designer could select. Most of these solutions integrate Wind and PV panels, and batteries for storage. Due to the high cost of a hydrogen storage component at that time, most of the solutions incorporated the exclusive use of batteries. The diesel fuel is highly priced in that location, which is why it was not part of the solutions. There are some past studies applied to HES design. Dipama et al. proposed a new variant of a GA for the optimization of two different power plant problems (Dipama, 2010). First, they worked on the design of a Cogeneration thermal plant. The objectives were the maximization of exergy efficiency and minimization of cost rate. Second, they worked on the design of an advanced steam power station. The objectives were the maximization of both, the efficiency and the net power output of the plant. For both designs, the proposed GA has appeared to be reliable, powerful, and robust when compared to previous research studies.

Meza et al. (Meza et al., 2009) examined a power generation expansion planning optimization problem. They proposed a multi-objective evolutionary programming algorithm (MEPA) for determining which, when, and where new generation units should be installed. A unit can be any one of the following: conventional steam units, coal units, combined cycle modules, nuclear plants, gas turbines, wind farms, and geothermal and hydro units. First, two objectives were considered: the minimization of investment and operation costs, and the environmental impact. Then, they added two other types (imports of fuel, and fuel price risks of the whole system) for a total of four objectives. The problem was nonlinear, mixed-integer, and considered an NP-Hard. They concluded that the system offered good quality solutions (close to the real Pareto set) when optimizing two objectives. Furthermore, the system was able to provide solutions when handling four objectives. However, it was not possible to compare the results with previous work because no past studies considered more than two objectives for these kinds of problems.

Niknam et al. (Niknam et al., 2011) proposed a new multi-objective modified honey bee mating optimization algorithm for the design of a PV-Wind-FC grid connected system. The proposed method showed better results than uni-objective optimization methods.

Ould et al. (Ould et al., 2010) used a multi-objective GA for analyzing a hybrid PV–wind-battery energy system by minimizing the annualized cost system and the loss of power supply probability in remote areas in Senagal. They compared three configurations in their study.

5.0 ENERGY SYSTEMS-RELATED OBSERVATIONS

Most of the systems are composed of PV and wind energy sources. These two energy sources match well together because both are intermittent and they complement each other. For

example, sometimes there is no wind, but the weather is sunny; PVs will compensate, and vice versa. However, their complementary roles are sometimes deficient especially at night-time because PV panels do not generate electricity. As a third component, hydrogen fuel cells are becoming more common within a standalone energy system framework. Previously, diesel and battery systems have been used. But fuel cells gained more popularity in the last couple of years because their prices are becoming more affordable, the technology is improving, and they are cleaner than batteries and diesel. The unused electricity generated from PV-wind is converted into hydrogen as an energy storage medium, which serves for operating FCs to regenerate electricity when needed (e.g. night-time). Moreover, hydrogen surplus can be directly used for industrial or transportation purposes. Thus, PV and wind systems are the most common renewable systems; however, hydrogen systems are increasingly used in hybrid energy systems. Almost all of the HES projects involved a PV component to convert the solar energy source into electricity. But PV has a lower conversion efficiency than solar thermal systems in hotter areas. PV systems become even less efficient in hot areas like deserts because of the high temperature. Consequently, studies should consider the use of solar thermal systems as an alternative to PV systems to benefit from solar energy sources in such areas. Another interesting observation is that previously HES was typically designed as standalone systems in remote areas. Currently, HES tends be integrated into existing grids which requires more complex models.

5.1 Optimization-related observations

simulation-based optimizations are declining because they require manual intervention for every run which makes them time consuming, tedious, and error prone. On the other hand, metaheuristics such as genetic algorithms are more attractive for the design of HES for several reasons. They are completely automated, they can generate results in a faster manner, and can handle complex non-linear models The energy research community has not fully utilized the most recent discoveries in the optimization field. There is a gap between the energy and optimization communities that should be bridged. This bridging will generate several positive impacts as follows when designing HES. First, HESs involve very complex optimization problems because of mixed type variables, non-linearity, and non-convexity, which make them difficult to solve with classical optimization methods; consequently, optimization metaheuristics such as genetic algorithms are more appropriate for optimal design of HESs. All HES design projects involve multi-objectives such as cost and pollution minimization, efficiency maximization, among others. Therefore, multi-objective metaheuristics are more promising for these types of problems. Despite these advantages, only a few studies have been completed with MOO metaheuristics methods for energy systems design. Even most of the state-of-the-art multi-objective optimization methods have not been utilized yet. Comparative studies of state-of-the-art multi-objective optimization methods can be found in Durillo et al. (2010) and Nebro et al. (2008). Moreover, multi-objective metaheuristics offer to HES designers multiple tradeoff solutions which are more practical and attractive for real-world engineering systems. The decision makers can select the solutions that best fit their needs. Furthermore, there are other newer MOO metaheuristics. For example, decision makers can be involved in the multi-objective optimization process by selecting intermediate solutions or adding a priori knowledge to an HES problem. Consequently, the metaheuristic will converge faster, and generate solutions which will be more ad hoc to the needs of the decision makers. Such methods are called interactive optimization methods; more details can be found in Branke et al. (2008). Also, most past studies have not presented a comprehensive sensitivity analysis. HES designs involve several uncertainties such as weather conditions, variations in the demand, and others. Therefore, HES design should always incorporate a sensitivity study to test the robustness of the HES. Alternatively, robust optimization methods can be used; these methods look for the most robust and optimal solutions at the same time. An extensive study of such methods can be found in Beyer HG and Sendhoff (2007).

6.0 CONCLUSIONS

Hybrid energy systems are attracting more attention because they can become more economical, environmentally cleaner, and can be installed in a distributed fashion. This literature review shows that most HESs are based on PV and wind energy sources because of their complementary roles. A challenge with solar and wind resources is their intermittency and not constantly available; usually they are complemented by diesel or batteries. However, diesel and batteries are decreasing while hydrogen systems are increasing. Hydrogen is cleaner than diesel and batteries, it is becoming cheaper, it can be reused for energy storage and it regenerates electricity when needed. Another conclusion in this paper is that previous studies focused on standalone systems usually installed in remote areas. Currently, the tendency is to have grid-connected HES. The simulation tools are more mature. However, several HES systems connected to the grid can generate grid congestion during peak hours. These congestion issues should be also considered when integrating multiple HES systems into a grid. Finding the optimal design of a hybrid energy system is a complex task because it involves multiple objectives, a large number of variables, heterogeneous energy technologies, uncertainties such as weather and demand, and other factors. This paper has reviewed the current trends to designing optimal hybrid energy systems. There are two main approaches for designing optimal hybrid energy systems. The first is simulation-based optimization. It permits the variation of different variables or parameters of hybrid energy systems in order to find an "optimal solution". These approaches require a designer's interaction for setting the parameters in order to find an "optimal" design. Therefore, this approach is arduous and time consuming. Moreover, every simulation generates only one solution. Furthermore, there is no automated support for helping or guiding the designer towards the optimum. The second approach uses optimization methods for designing hybrid energy systems. The current trend is the use of metaheuristic algorithms for HES optimization design because they obtain automatically optimal or close to optimal solutions. They can handle a high number of mixed type variables (i.e., real vs. discrete variables). Furthermore, metaheuristics can handle complex problems such as energy design systems which are not linear, nor convex. Therefore, metaheuristics are more suitable for solving hybrid design energy problems. In addition, all HES involve multiple competing objectives such as cost minimization and energy maximization which can be solved by multi-objective optimization metaheuristics. MOO metaheuristics generate multiple tradeoff solutions that are more practical and attractive for real-world engineering systems. Despite these advantages, this literature review has shown that very limited work has been conducted in the past with multi-objective optimization metaheuristics for energy systems design. Furthermore, the used multi-objective optimization metaheuristics were not state-of-the-art. Therefore, the design of optimal HESs requires more interaction between both energy and multi-objective optimization research communities to fill this gap. Other more recent MOO metaheuristics methods should be explored such as MOO robust optimization and MOO interactive optimization methods. Robust optimization targets optimal and robust solutions at the same time, while interactive optimization takes input from decision makers while searching optimal solutions.

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