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Techno-economic feasibility of photovoltaic, wind, diesel and hybrid electrification systems for off-grid rural electrification in Colombia

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ABSTRACT

Electrification to rural and remote areas with limited or no access to grid connection is one of the most challenging issues in developing countries like Colombia. Due to the recent concerns about the global climatic change and diminishing fuel prices, searching for reliable, environmental friendly and renewable energy sources to satisfy the rising electrical energy demand has become vital. This study aims at analyzing the application of photovoltaic (PV) panels, wind turbines and diesel generators in a stand-alone hybrid power generation system for rural electrification in three off-grid villages in Colombia with different climatic characteristics. The areas have been selected according to the "Colombia's development plan 2011–2030 for non-conventional sources of energy". First, different combinations of wind turbine, PV, and diesel generator are modeled and optimized to determine the most energy-efficient and cost-effective configuration for each location. HOMER software has been used to perform a techno-economic feasibility of the proposed hybrid systems, taking into account net present cost, initial capital cost, and cost of energy as economic indicators.

1. Introduction

Energy is considered as one of the central indexes of social and economic development of any country. Nowadays, almost 80% of the global energy demand is met by means of fossil fuels, resulting in significant environmental impacts [1]. Conventionally, electricity is generated in large thermal power plants and is then transported through high-voltage and medium-voltage distribution grids [2,3]. However, greenhouse gas (GHG) emissions, the main source of global warming, as well as the air pollution raise a great deal of concerns mainly caused by continuous burning of fossil fuels for electricity generation [4–6]. On the other hand, rapid depletion of fossil fuel resources on a global scale and progressive increase in energy demand and fuel price are other motives to reduce the reliance on fossil fuels [7]. In order to tackle the aforementioned obstacles related to the conventional power generation methods and cater the present energy demand, the development of power generation systems based on renewable energy is attracting attention as a green solution [8–11].

Renewable energy sources (RES) are virtually so abundant that they can supply more than the global energy demand. They also can be utilized without any cost for the resource [1,3]. Nonetheless, the potential of this clean energy has not been fully exploited due to technical and economic barriers, and the resource availability. During the last few decades, RES have shown growing importance in power generation owing to their emission free, environmental friendly and inexhaustible nature [12,13]. Furthermore, a large proportion of the world's population lives in remote rural areas [2], especially in developing countries like Colombia, and these areas are partially integrated with the electrical grid. This poor electricity distribution is mainly due to geographical inaccessibility, rugged terrains, lack of electrical infrastructure, and high required economic investment for installing large grid connected power lines over long distances to provide electricity for regions with a low population [14,15]. As a result, Distributed Generation (DG) technologies based on renewable energy, called stand-alone hybrid renewable energy system [16,17], can be as suitable options for such remote areas [3,18]. In recent years, owing to the technological improvements and governments' policies to promote RES utilization resulting in significant cost reductions, these units have

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Nomenclature

C	cost ($)
COE	levelized cost of energy ($/kWh)
CRF	capital recovery factor (−)
E	energy (kWh/year)
f	energy fraction (−)
i	annual real interest rate (−)
N	system lifetime (year)
NPC	net present cost ($)
R	remaining cost ($)
RF	renewable fraction (−)
TAC	total annualized cost ($)
TOC	total operating cost ($)
$	American dollar

Subscripts

ann	annualized
DG	diesel generator
f	fuel
OM	operating and maintenance
R	replacement
S	salvage
tot	total
w	wind

become commercially viable alternatives for electrification in remote areas. In Australia, as an instance, community grants, cost sharing incentives, transition incentives, tax incentives, and environmental markets, are examples of incentives applied on renewable energies [19,20]. In Colombia, the policies include tax exemption or reductions and, till 2013, they were provided by the Ministries of Environment, Housing and Territorial Development, and the DIAN (National Tax Entity) [21]. Since 2014, according to the law 1715, for non-grid access zones, the supporting policies are regulated by the Ministry of Energy and Mines. The policies that have been approved since then include the reductions in the income tax for a period of 5 years, accelerated depreciation of assets, exclusion of VAT (value added tax) on goods related to the project and exemption from customs tariff [22].

However, in contrast to the conventional energy sources, consistency of supply is a significant issue associated with most RES due to their intermittent characteristics under varying atmospheric conditions which considerably influence the resulting energy production [1,4,23]. Consequently, in an effort to overcome the variability of the output of renewable energy systems and to provide a reliable energy supply, which sufficiently meets the demand, renewable energy systems can be combined with non-renewable energy systems and/or energy storage technologies [8,9,24–26]. There has been a vast amount of research on standalone RES and hybrid power systems, which integrate two or more different types of renewable and low carbon technologies (e.g. photovoltaic, wind turbines, fuel cells, diesel generator, etc.). Givler and Lilienthal [27] performed a case study of Sri Lanka in order to compare PV/diesel hybrid and stand-alone solar systems. The study indicated that, as energy demand increases, the PV-diesel hybrid becomes more efficient over single solar technology. Valente and De Almeida [17] performed an economic analysis on hybrid PV/diesel system and demonstrated that over a 20-year period, the hybrid system results in reduction of fuel consumption and operation and maintenance costs, while ameliorating the quality of service. Among various types of RES technologies available on the market, solar and wind energy systems are considered as promising power generating sources due to their availability and topological advantages in remote areas [3,15,28,29]. The intermittent nature of solar and wind resources can be mitigated to a large extent via an optimal integration of these resources to meet the load for extended time periods. The use of solar and wind energy systems are becoming more economically justifiable and technically feasible owing to the manufacturing cost reduction, and extensive research and development in RES exploitation for power generation [3,4,30].

To date, the viability and performance studies of PV systems and PV-based hybrid systems have been investigated in a number of research studies, based on the techno-economic analysis [31,32]. Abdullah et al. [33] stated that hybrid power schemes are more sustainable in terms of supplying electricity to a Tele center in rural area compared to a stand-alone PV system due to lack of solar irradiance. Girma [34]studied a PV/diesel hybrid system where a diesel generator was used as a back-up system in case of scare solar irradiation. The author found that the initial cost of the hybrid system is higher than a stand-alone diesel generator system, while PV covers 95% of the total energy generation of the system. It was concluded that the payback time for the investment cost of the PV/diesel/battery hybrid system is about 2 years, assuming an energy cost of 0.468 $/kWh.

Moreover, design and control logics of such hybrid systems have been investigated in many works including those dedicated to wind-diesel system using statistical data of loads and wind speed [35], PV-diesel-battery system [36], and solar–wind hybrid power system [37].

Using a photovoltaic/wind/diesel hybrid system can be a more reliable approach for supplying electrical demand of remote areas as compared to photovoltaic-only/wind-only systems [38,39]. This is due to the fact that reliance on a single technology generally results in an over-sizing of the system, thereby increasing the plant initial costs. On the other hand, combining a diesel generator with photovoltaic and/or wind system is to guarantee the minimum diesel fuel consumption and consequently minimizing operating costs and carbon footprint of the system [26,40,41]. Shaadid and Elhadidy [42]studied the techno-economic feasibility of hybrid PV-diesel-battery system for a building with 620 MWh/year energy demand. The system consisted of 80 kW PV and 175 kW diesel with the cost of energy (EC) as 0.149 $/kWh. Al-Badi [43]evaluated the techno-economic feasibility of running a hybrid wind–PV–diesel power system to satisfy the load of Al Hallaniyat Island.

Nonetheless, due to multiple possible combinations of RES and non-renewable energy sources, as well as dependency on many factors such as the load demand, seasonal availability of energy sources, costs of components and fuel, and governments' policies reaching the best solution is complex and requires to be fully studied [20,40,41]. As a result, several optimization procedures and software have been developed and examined lately to assess the technical and economic potential of various hybrid renewable technologies to simplify the hybrid system design process and maximize the use of the renewable resources. A number of studies aiming at determining the optimal hybrid system for different electrical loads have been reported in the literature [44–48]. In a study by Koutroulis et al. [49], the optimal size of a standalone hybrid system while achieving the least cost using genetic algorithm was conducted and verified the superiority of hybrid solar-wind systems compared to solar/wind single systems. The possible system combinations were characterized by considering