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A hybrid renewable energy system for a North American off-grid community

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ABSTRACT

Canada has many isolated communities that are not connected to the electrical grid. Most of these communities meet their electricity demand through stand-alone diesel generators. Diesel generators have economic and environmental concerns that can be minimized by using hybrid renewable energy technologies. This study aims to assess the implementation of a hybrid energy system for an off-grid community in Canada and to propose the best hybrid energy combination to reliably satisfy electricity demand. Seven scenarios were developed: 1) 100% renewable resources, 2) 80% renewable resources, 3) 65% renewable resources, 4) 50% renewable resources, 5) 35% renewable resources, 6) 21% renewable resources, and 7) battery-diesel generators (0% renewable resources). A case study for the remote community of Sandy Lake, Ontario, was conducted. Hybrid systems were chosen to meet the requirements of a 4.4 MWh/day primary load with a 772 kW peak load. Sensitivity analyses were carried out to assess the impact of solar radiation, wind speed, diesel price, CO_2 penalty cost, and project interest rate on optimum results. A GHG (greenhouse gas) abatement cost was assessed for each scenario. Considering GHG emission penalty cost, the costs of electricity for the seven scenarios are $1.48/kWh, $0.62/kWh, $0.54/kWh, $0.42/kWh, $0.39/kWh, $0.37/kWh, and $0.36/kWh.

1. Introduction

The population of the world is increasing daily and people desire a high standard of life. As a result the world's economic and industrial sectors are growing and the demand for energy is increasing over time to satisfy needs. However, about 1.2 billion people in the world have no access to electricity. Providing reliable and cost-effective electricity to them is a major challenge. Grid extension still remains the preferred mode for the electrification of rural areas. But extending a central electricity grid to geographically remote and sparsely populated rural areas is neither always financially viable nor practically feasible. In such cases, off-grid options can be helpful [1].

There are 175 aboriginal off-grid communities in Canada. Most of them use diesel generators to meet their electricity demands. Diesel generators have many disadvantages. Diesel is a fossil fuel, and burning fossil fuels produces substantial GHG (greenhouse gas) emissions, which cause global warming. Moreover, during long-distance transportation of fuels by plane, truck, or barge, there is always a risk of fuel spilling, which poses a threat to the environment. Lastly, generators make noises that can be irritating, especially in remote and quiet communities.

Renewable energy resources (solar, wind, hydro, and tidal) are promising alternate means of generating power that can overcome the problems of diesel generators. Renewable energy is considered a green or clean energy because it does not produce toxins or pollutants that are harmful to the environment. Fossil fuels are not easily stored, and fossil fuels are depleted through consumption. But the supply of renewable resources is unlimited and has the potential to replace conventional energy sources. However, the single use of renewable resources to generate energy, such as a stand-alone wind turbine or a stand-alone PV cell, is not viable since the resource supply (wind, sunlight) is not continuous. A combination of resources with a back-up unit, or a hybrid system, is sustainable and economical and could address these issues [2–8]. Operating a diesel generator with a hybrid system increases system sustainability and lowers energy production costs. Optimizing the component sizes of a hybrid system in order to meet load

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requirements with minimum investment and operating costs is the system's biggest challenge [2].

Many studies have been carried out to find the best energy combination of a hybrid energy system. The combination depends on the available renewable energy resources and the load demand of the particular location. Using HOMER software, Li et al. [9] performed a feasibility study of a hybrid wind-PV-battery power system for a household in Urumqi, China. They found that with 72% solar and 28% wind, the total NPC (net present cost) is reduced by 9% compared to PV-battery and 11% compared to wind-battery power systems. A similar trend was observed in the study by Kusakana and Vermaak [10]. They designed a hybrid PV-wind renewable system and compared it with a pure PV, a pure wind, and a diesel generator. They found that the COE (cost of electricity) was $0.372/kWh, $0.393/kWh, $0.53/kWh, and $1.34/kWh for hybrid PV-wind, pure PV, pure wind, and pure diesel generator, respectively. The initial cost of the diesel generator is lower than that of either solar PV or wind turbine, but its maintenance and operational costs are high [11]. Kusakana and Vermaak [10] reported a higher COE for the diesel generator compared to the COE reported by Adaramola et al. [11] and Fadaeenejad et al. [7]. Comparatively much higher diesel price and O&M (operation and maintenance) cost for the diesel generator led to increase the cost of energy.

A hybrid renewable energy system was designed by Rohani and Nour [12] for a remote area in Ras Musherib in western Abu Dhabi. Diesel generators were incorporated with wind and PV. Different combinations of wind turbines, PV, batteries, and generators were evaluated in order to determine the optimal combination of a 500 kW hybrid system based on the lower net present cost. Modeling, optimization, and simulation were performed by HOMER. The results showed that the hybrid system with 45% from renewable sources (15% photovoltaic and 30% wind) had the lowest net present cost. The contribution of wind is higher than solar PV because the location has healthy wind resources (wind speed, 4.95 m/s) and high PV costs. Compared to emissions from diesel generators, CO_2 emissions were reduced by 37% with this hybrid system. The greater proportion of renewable energy decreases CO_2 emissions because of the lower fuel consumption but increases capital costs.

A similar hybrid system with a larger capacity (19.4 MW) was proposed by Zubair et al. [13]. The authors designed a wind-PV-diesel hybrid system for the coastal area of Bangladesh. In the coastal areas, grid connection is not available and grid extension is not feasible, but renewable resources, especially wind, are abundant; the average wind velocity at a height of 50 m is 6.74 m/s. It was shown that a 100% renewable energy-based system is not financially viable, but a wind-PV-diesel hybrid system can be cost effective. The optimum combination for lowest energy costs was found with 55% wind, 14% PV, and the rest from a diesel generator. The CO_2 emissions for this system were reduced by 69% compared to a conventional diesel generator power system.

Ngan and Tan [14] analyzed the potential implementation of a hybrid PV-wind-diesel system in Johor Bahru, a city in southern Malaysia. Due to low wind speed in that location, most of the electricity comes from PV and a diesel generator. With this hybrid system, CO_2 emissions were reduced by 35%. The techno-economic feasibility of stand-alone hybrid PV-diesel energy systems was analyzed by Ghasemi et al. [15] for remote rural areas of eastern Iran where solar radiation of 5 kWh/m^2/day is very common. They showed that stand-alone hybrid PV-diesel energy systems are preferable to stand-alone diesel generator that produces 87,144 kg of carbon dioxide and 2349 kg of other pollutant gases in a year.

Fleck and Hout [16] compared a stand-alone small wind turbine system with a single-home diesel generator system. The main focus was to compare the GHG emissions of the two systems. The emissions were calculated over the whole life of both systems, which provide the same amount of energy. The results showed that the wind turbine system offered 93% reduction of GHG emissions compared to the diesel generator system [16].

There is limited study on renewable energy options for remote Canadian communities. Although there are some studies conducted for hybrid renewable energy system around the globe, no study is reported to design a hybrid energy system for a community in Canada. Most of the studies worked on electricity production for domestic purposes and do not consider the electricity demand for industrial, commercial, and community purposes for the socio-economic development of the whole community. Moreover, very few studies considered penalty cost for emitting GHG (greenhouse gases) into the atmosphere. This study is aimed at bridging the knowledge gap in current literature. The design of a hybrid system is very much location specific which depends on the local wind speed, solar irradiation, diesel price, etc. No earlier study is reported to understand the effect of CO_2 penalty price on the renewable energy fraction of the system. Through a sensitivity analysis, the current study shows how the renewable fraction is changing with the change in CO_2 penalty cost. To make investment decisions by the policy makers and stockholders, it is necessary to conduct a comprehensive and independent study on hybrid renewable energy systems. The purpose of this study is to find the best combination of renewable energy systems from the available resources for a particular off-grid location in Canada. The electricity production, techno-economic assessment, and emissions assessment for different hybrid energy systems were carried out and compared for the selected community. It is expected that the optimal hybrid energy system can provide an environmentally friendly and cost-effective solution for the electricity supply for the community. The development of seven different scenarios for hybrid energy systems based on combinations of different energy sources for a remote Canadian community was the key objective of this study.

2. Methodology

To achieve the objective, the methodology included: (1) choosing an off-grid site, (2) identifying the available resources and estimating potential demand for the selected site, (3) modeling the system (i.e., modeling annual electricity production, economic assessment, and emissions assessment) by considering different scenarios with HOMER software [17], and (4) selecting of the most cost-efficient scenario as the optimal hybrid energy system.

Fig. 1 shows the detailed steps of the analysis. Before starting the analysis with HOMER, some initial assessments were done to determine the location of the hybrid energy system. The location should be at a potential source of renewable power (i.e., solar, wind, hydro, etc.) Then the load demand is estimated for the location; this tells us how much electrical energy to generate. After that, the components of the hybrid system are selected based on potential resources available. All of the necessary component data such as cost, size, lifetime, and resource data such as wind velocity and solar insolation throughout the year were collected. Then a simulation was carried out by inputting the system constraints in HOMER, and finally an optimization was performed, with varying factors to satisfy the load demand with minimum net present cost and cot of energy.

HOMER, a popular analytical tool for optimizing energy systems, was used in this study. HOMER stands for "Hybrid Optimisation Model for Electric Renewable" and was developed by the NREL (National Renewable Energy Laboratory) in the USA. A wide variety of technologies such as PV, wind, hydro, fuel cells, and boilers can be addressed with HOMER. It can handle different types of loads such as AC/DC, thermal, and hydrogen and can perform hourly