A Hybrid Renewable Energy System for a North American Off-grid Community

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Highlights

- Modeling of hybrid renewable energy systems for an off-grid community
- Seven scenarios were developed based on various renewable energy fractions
- Cost of electricity is the highest for 100% renewable fraction scenario

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- CO_2 emissions are reduced by 1232 tonnes/yr by switching from diesel to renewables
- Use of different sensitivity parameters to see the impact on electricity cost

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 greenhouse gas (GHG) 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.

Key Words: Hybrid energy system; HOMER; off-grid; renewable energy.

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 greenhouse gas (GHG) 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 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 net present cost (NPC) is reduced by 9% compared to PV-battery and 11% compared to wind-battery power systems. A similar trend was observed in Kusakana et al.'s work [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 cost of energy (COE) 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 et al. [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 operation and maintenance (O&M) cost for the diesel generator led to increase the cost of energy.

A hybrid renewable energy system was designed by Rohani et al. [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. Modelling, 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 feasible and grid extension is not available, 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 et al. [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 analysed 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 et al. [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 greenhouse gases (GHG) 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.

Figure 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.

Figure 1: Detailed steps of the analysis in this study

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 National Renewable Energy Laboratory (NREL) 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 simulations. It has been used to analyse off-grid electrification issues in the developed and developing countries [1].

The required data for this software include component specifications, meteorological data, electrical loads, and costs. HOMER generates optimized results for thousands of feasible hybrid renewable energy systems and sorts them based on lower net present cost. Since HOMER repeats optimization processes for each input value, it is possible to analyze the effect of various inputs like the effects of variations in wind speed or solar radiation. The program makes analyzing and comparison easier for various types of grid-connected and off-grid design options. It assists in inspecting and comparing diverse electricity generation approaches through assorted technologies as well. HOMER can also be used to perform sensitivity analyses [13]. For sensitivity analyses, HOMER needs to be provided with a range of components' costs and availability of resources as the sensitivity values.

In this study, different scenarios using solar, wind energy, and diesel generators were considered. Figure 2 shows a hybrid energy system. It contains renewable energy sources, diesel generator, electric load, PV, wind turbines, battery, and converter**.**

Figure 2: Hybrid energy system

3. Site Selection and Resource Assessment

3.1. Site Description: Sandy Lake

The Sandy Lake First Nation community was selected for the analysis of a hybrid energy system as this location has significant renewable resource potential that can replace the existing stand-alone diesel generators. The purpose of this study is to meet the electricity demand in a way that is cost competitive and environmentally friendly. Sandy Lake is located in the Kenora District, 227 kilometers northeast of Red Lake, Ontario. Its geographical coordinates are $53^{0}3'$ N, $93^{0}20'$ W. The total population and number of houses are 2474 and 460, respectively. This is an off-grid region of Ontario. This place has good wind energy potential and solar resources to produce electricity with wind turbines and photovoltaic panels [18].

3.2. Estimation of Demand Load

The data for load demand calculations, such as total number of houses (460) and total population (2474), are taken from the Aboriginal Affairs and Northern Development Canada website [18]. Electricity consumption is higher in summer than in winter because fans and air conditioners (in medical centre and industries) are used in summer. Electricity consumption data for Sandy Lake are divided into four sectors: domestic, industrial/commercial, medical, and school. The domestic load was calculated for 460 houses on the assumption that each house has three lights, one television, one refrigerator, and one ceiling fan. The industrial/commercial sector includes 15 shops, 1 community centre, 8 small manufacturing units, and 8 street lights with a total power consumption of 5.03 kW. The medical centre and the school consume 0.85 kW and 0.45 kW, respectively. Since electricity consumption is seasonal, the demand was estimated separately for two distinct seasons, summer (April to October) and winter (November to March). The total load demand is calculated for each hour of the day and the value is inserted in HOMER. Electricity demand varies throughout the day, and it was assumed that the peak demand occurs at night from 1900 to 2300 h. The primary load is estimated to be 4.4 MWh/day with 772 kW at its peak.

3.3. Resource Assessment

3.3.1. Solar Energy

Monthly solar insolation data were taken from the NASA Surface Meteorology and Solar Energy database. The annual average solar insolation is 3.24 kWh/m^2/day at Sandy Lake. The average clearness index, a measure of the atmosphere's cleanness, was found to be 0.505. Figure 3 shows the monthly solar radiation and clearness index. Sandy Lake has the potential for solar energy from April to August, and a considerable amount of PV power can be extracted.

Figure 3: Monthly solar radiation and clearness index at Sandy Lake (generated by HOMER, using data from [19])

3.3.2. Wind Energy

Ontario is one of the leading wind energy generating provinces of Canada and has a capacity of more than 1700 MW wind energy connected to the province's electricity grid. Wind speed is high at Sandy Lake during the fall (September-November). Monthly average wind resource data were collected from the Canadian Wind Energy Atlas database [20] based on the longitude and latitude of the location for a height of 50 m. Monthly average wind speed data are shown in Figure 4.

The annual average wind speed was found to be 5.06 m/s [20]. The wind speed variation over a day (diurnal pattern strength) is 0.25 and the randomness in wind speed (autocorrelation factor) was considered to be 0.85.

Since wind speed is not steady throughout the year, it was necessary to find the probability density distribution of the wind speed to calculate the mean power from a wind turbine. The Weibull distribution shows a good fit to wind data. In the Weibull distribution expression, k is a factor that depends on annual wind speed distribution data and determines the shape of the distribution curve. In this study, the value of k has been taken as 2.

Figure 4: Wind speed variation throughout the year at Sandy Lake

To better understand the resource availability at Sandy Lake, the annual average solar insolation and wind speed data were compared (see Table 1) for different regions around the globe where hybrid renewable energy systems are proposed in the existing literature.

Table 1: Comparison of resource availability at different regions around the globe

3.3. Assessment of Components

Hybrid energy systems consist of solar PV panels, diesel generators, wind turbines, batteries, and converters. To find the optimum COE (cost of energy), different cost parameters, i.e., first cost, operation and maintenance costs, and component replacement costs, are used. Capital costs, replacement costs, and maintenance costs for each of these components are tabulated in Table 2. All currency figures in this paper are expressed in USD and the base year is 2015 unless otherwise noted. Costs were adjusted to the year 2015 using historical inflation rates [21].

Table 2: Cost parameters used for different components of a hybrid system

In this study, the PV array was assumed to be equipped with a maximum power point tracker (MPPT). In reality, PV array's output depends on the voltage to which it is exposed. MPPT makes sure that the array's voltage is equal to the voltage at which the output power is maximized. Hence, in this study, PV array's output power was assumed to be directly proportional to the solar radiation reaching the panels and independent of the voltage to which it is exposed. Efficiency at standard test conditions, derating factor, and lifetime of the PV arrays was assumed to be 11.9%, 90%, and 20 years, respectively [9].

Since the annual average wind speed at Sandy Lake is 5.06 m/s, the ReDriven 10 kW and ReDriven 20 kW wind turbines were chosen for this study. Both turbines have a cut-in speed of 2 m/s and a cut-out speed of 18 m/s [23]. The turbine lifetime was assumed to be 20 years and hub heights were assumed to be 30 meters [23]. Data required for these two turbines' (ReDriven 10 kW and ReDriven 20kW) wind curves were taken from ReDriven Power Inc. and Better Generation's website [25, 26, 27].

A Kirloskar diesel generator with 160 kW rated power was considered in this study. HOMER uses a linear correlation and fuel curve for fuel consumption calculations, and in this study the slope and the intercept of the fuel curve were taken to be 0.2486 L/h/kW and 0.0161 L/h/kW [28], respectively. Diesel price is $0.9/L for Ontario [29]. The generator is connected to an AC output with a lifetime of 15000 hours and a 25% minimum load ratio. In this study it was assumed that diesel will be supplied to the hybrid energy system location fom the local retail stations. Diesel price may vary with the variation in exchange rate. Due to scarcity and difficulty in transportation in winter, fuel price may go up. To study the effect of diesel price on cost of electricity, diesel price has been varied between $0.72/L and $1.08/L. The highest price, $1.08/L represents the diesel price (including the cost of transportation) during adverse situations.

Batteries are used as a backup in the system and to maintain a constant voltage level during peak loads or a shortfall in generation capacity [1]. The battery chosen in this study is a 12 V battery with a nominal capacity of 83 Ah. It has a lifetime throughput of 9,645 kWh [9]. Each battery string was assumed to contain 12 batteries.

A converter is required to convert from AC-DC or DC-AC. The lifetime of the converter was assumed to be 15 years, inverter efficiency as 90%, and rectifier efficiency as 85% [9].

HOMER can model two load dispatch strategies, cycle charging and load following. Under the load following strategy, renewable resources charge the battery; the generator only produces enough power to serve the load. Under the cycle charging dispatch strategy, the generators produce more power than needed and the surplus electricity is used in charging the battery bank. Since the cycle charging strategy is more suitable for large-scale systems [30], it was used in this study.

4. Results and Discussion

4.1. Scenario Analysis

Seven scenarios were studied to observe the impact on emissions and electricity cost as the renewable fraction increases. The scenarios are as follows:

1) Scenario 1: 100% renewable resources
2) Scenario 2: 80% renewable resources
3) Scenario 3: 65% renewable resources
4) Scenario 4: 50% renewable resources
5) Scenario 5: 35% renewable resources
6) Scenario 6: 21% renewable resources
7) Scenario 7: Battery-diesel generator

Based on the number of input parameters, each scenario was run for 27 minutes to 3 hours 17 minutes for the simulation. A personal computer of Intel (R) Core (TM) i5 processor with 2.50 GHz speed, 6.00 GB ram and 64-bit operating system was used for the research.

The energy systems designed for this study are assumed to have a lifetime of 25 years and an annual interest rate of 6%. Component combinations for each scenario are shown in Table 3.

Table 3: Component combinations for the seven scenarios considered in this study

4.1.1. Electricity Production

Total electricity production, excess electricity generation, and cost of electricity (COE) for each of the seven hybrid scenarios have been tabulated in Table 4. Excess electricity is generated whenever the system produces more electricity than the load demand and the batteries can't absorb all the surplus electricity. Of the seven scenarios, scenario 6 (21% renewable resources) was found to generate the least excess electricity and scenario 1 (100% renewable resources) was found to produce the most excess electricity. This is mainly due to the production of excess power during high wind and high solar radiation. Scenario 7 (battery-diesel generator) produces 10.7% excess electricity without any solar or wind power. This is because of higher rated power of the diesel generator than the load demand.

Table 4: Electricity production, excess electricity, and cost of electricity (COE) for seven scenarios

For the 100% renewable system, the diesel generator does not produce any electricity, as expected, and 54.40% and 45.60% of electricity are produced by the PV and wind turbine, respectively. In contrast, for battery-diesel generator system all electricity is produced from diesel generator. Electricity is produced by wind turbine and diesel generator for 50% renewable system. For the other four systems (i.e., the 80%, 65%, 35%, and 21% renewable systems), electricity is produced from all components but with different combinations (see Table 4). The solar fraction is reduced more rapidly than the wind fraction when the system's renewable fraction decreases. The energy production throughout the year is shown in Figure 5. The trend of electricity production is similar to the trend of wind resources (shown in Figure 4). This is expected because wind resources at Sandy Lake exceed solar resources.

Figure 5: Monthly electricity generation for different scenarios. (a) 100% renewable resources; (b) 80% renewable resources; (c) 65% renewable resources; (d) 50% renewable resources; (e) 35% renewable resources; (f) 21% renewable resources; (g) battery-diesel generator (0% renewable resources)

4.1.2. Economic Analysis

Cost is an important factor in the implementation of any system. The cost analysis for the seven scenarios is shown in Figure 6. Figure 6 shows the total net present cost and the partial net present cost based on different components. The 100% renewable system has the highest net present cost of the seven scenarios. As wind turbine and PV panels have a higher capital cost and a lower running cost, the total cost for a 100% renewable system is higher because the fractions of wind and PV are higher. In contrast, a diesel generator has a lower capital cost and a higher running cost. The higher running cost is due to the cost of fuel. This is why a stand-alone diesel system also has a higher total cost compared to the diesel generator cost of the other scenarios. For 50% scenario, based on the resource availability, HOMER selects hundred 10 kW wind turbines and a 480 kW diesel generator to satisfy the given load with least net present cost. No PV is selected for this case. The cost-effectiveness of a system configuration is based on its net present cost [17]. For 50% renewable fraction scenario, wind turbine/diesel generator configuration (net present cost: $11.84 million) wins over the other configurations, including PV/wind turbine/diesel generator (net present cost: $ 11.86 million). But for 80% scenario, sixty 10 kW wind turbines, a 480 kW diesel generator, and 700 kW PV panel were selected (see Table 3). The NPC of 100 (units) 10 kW wind turbines and 60 (units) 10 kW wind turbines are calculated to be $6.47 million and $3.88 million, respectively. The NPC of 700 kW PV panels is $3.37 million. The NPC of diesel generator is reduced at 80% renewable energy fraction as the diesel consumption is reduced by 76% compared to 50% renewable energy fraction scenario. PV/wind turbine/diesel generator configurations (see Table 3) were selected as most cost efective for the 21%, 35%, 65% and 80% renewable fraction scenarios based on the net present cost of the system.

To check the feasibility of stand-alone PV and stand-alone wind turbine, the model was run for two additional systems where all the renewables are solar and wind, respectively. Solar and wind resources are unpredictable and can be unreliable. A stand-alone PV system or a wind energy system cannot generate electricity throughout the year when there are cloudy days or when there is relatively high cut-in wind speed [11]. The net present cost for the stand-alone PV and stand-alone wind systems are found to be $77.38 million and $42.73 million, respectively which are much higher than any of the scenarios developed in this study. The COE of stand-alone wind system ($2.14/kWh) is comparatively lower than the COE of stand-alone PV system ($3.87/kWh) because at Sandy Lake potential for solar energy (3.24 kWh/m^2/day) is much lower than wind energy (5.06 m/s). For stand-alone PV or Wind, the system has to be oversized to make it reliable which leads to increase the net present cost and cost of electricity. A PV-wind hybrid system gives a better solution compared to stand-alone PV or stand-alone wind system. When there is less solar insolation, electricity will be produced from wind and when there is insufficient wind speed electricity will be produced from solar energy. For a better reliability a PV-wind-diesel hybrid system could be used.

Figure 6: Net present cost of components for different scenarios

4.1.3. Emissions Analysis

Different types of pollutants (CO_2, CO, SO_2, NO_X, particulate matter) are emitted during the combustion of fossil fuel to produce electricity. A transparent quantification of emissions is required to determine the optimum configuration among the scenarios that is economically and environmentally viable for a community. This study considers operational emissions but not the emissions from equipment production. The combustion of diesel is the only source of operational emissions. Emissions were calculated using emission factors and diesel consumption per year. Emission factors are based on the diesel properties that are shown in Table 5.

Table 5: Diesel properties [17]

Table 6 shows the emissions analysis of all the scenarios. There are no emissions in scenario 1, the use of 100% renewable resources, as this configuration does not use fossil fuel. Scenario 2, the 80% renewable resources system, consumes 212.81 L/day diesel with yearly emissions of 204 tonnes of CO_2. Emissions are highest (1,232 tonnes/yr of CO_2) for a stand-alone diesel generator system with a diesel consumption of 1,282 L/day. Scenario 4, the use of 50% renewable resources, showed that carbon dioxide emissions can be reduced by about 56% compared to the stand-alone diesel generator scenario. The emissions of carbon dioxide and other pollutants decrease as the renewable fraction increases (or diesel consumption decreases).

Table 6: Emissions analysis for different scenarios*

In considering the emissions for different scenarios, the 100% renewable resources scenario could be the most attractive. But the selection of any configuration also depends on the electricity production cost.

In this study, GHG emission and renewable resource use are taken into account by considering an emission penalty of $13/tonne [31, 32] of CO_2 emission. The COE for all the scenarios is tabulated in Table 7.

Table 7: Cost of electricity (COE) after carbon tax addition for different scenarios

4.2. Sensitivity Analyses

Sensitivity analyses were performed to see the impact of various parameters on electricity production costs. For the 21% renewable resources scenario, four independent parameters (solar radiation, wind speed, diesel price, and interest rate) were selected and varied by ±20%. The base case values of solar radiation, wind speed, diesel price, and interest rate were 3.24 kWh/m^2/day, 5.06 m/s, \$0.9/L, and 6%, respectively. The results of the sensitivity analysis are depicted in Figure 7.

An increase in the diesel price increases the cost of electricity (\$/kWh), because the increased diesel price leads to an increased diesel generator operating cost. This parameter has the largest impact on the price of electricity. The COE changes from \$0.327/kWh to \$0.407/kWh for a variation in diesel price from -20% to 20% (i.e. \$0.72/L to \$1.08/L). Wind speed was found to be the second most dominating factor, and an increase in wind speed causes a decrease in the COE. Varying the interest rates does not have a large impact on the cost of electricity production. The shift in discount rate from 6% to 7.2% results in a \$0.004 increase in the cost of electricity. The impact of solar radiation has negligible impact on electricity production costs.

Figure 7: Sensitivity analysis for the 21% renewable resources scenario

Carbon penalty cost (\$/tonne) and diesel price (\$/L) were varied to see the impact on the renewable percentage of the system. The base case values for carbon penalty cost and diesel price were taken as \$13/tonne, \$0.90/L, respectively. For the analysis, minimum renewable fraction was used as 0% so that HOMER can choose any renewable fraction from 0% to 100%. Table 8 shows how the COE changes when diesel fuel price and CO_2 penalty cost are varied. The change in renewable fraction is shown in Table 9 when diesel price and CO_2 penalty cost are varied. An increase in diesel price increases the cost of electricity (COE) and renewable fraction (see Tables 8 and 9). A higher diesel price increases the net present cost which leads the system to produce more electricity from renewables. At \$1.30/L diesel price and \$13/tonne CO_2 penalty cost, the renewable fraction is increased to 45% from 21% at \$0.90/L diesel price. CO_2 penalty cost has insignificant impact on COE as CO_2 penalty cost is a very small component (<1.5%) of the total cost of the system. When the CO_2 penalty cost is increased from \$13/tonne to \$50/tonne at a diesel price of \$0.90/L, the COE is increased from \$0.37/kWh to \$0.39/kWh. On the other hand the renewable energy fraction is increased from 21% at a CO_2 penalty cost of \$13/tonne to 30% at a CO_2 penalty cost of \$35/tonne when the diesel price is \$0.90/L.

Table 8: Sensitivity analysis to check the cost of electricity (COE) of the system

Table 9: Sensitivity analysis to check the renewable fraction of the system

5. Conclusions

Sandy Lake is an off-grid community in Canada that meets its electricity demand using diesel generators. Diesel generators have a number of negative impacts on the community and can be replaced with a hybrid renewable system. A feasibility study was conducted by assessing seven hybrid energy systems - 100% renewable resources (scenario 1), 80% renewable resources (scenario 2), 65% renewable resources (scenario 3), 50% renewable resources (scenario 4), 35% renewable resources (scenario 5), 21% renewable resources (scenario 6), and battery-diesel generator (scenario 7). Among the seven scenarios, scenario 7 was found to have the lowest cost of electricity (COE) (\$0.34/kWh). But this system emits 1,232 tonnes/year of CO_2. On the other hand, scenario 1, scenario 2, scenario 3, scenario 4, scenario 5, and scenario 6 have COEs of \$1.48/kWh, \$0.61/kWh, \$0.53/kWh, \$0.42/kWh, \$0.39/kWh, and \$0.37/kWh, respectively. But these six scenarios include a renewable fraction and emit fewer greenhouse gas (GHG) emissions than scenario 7. In considering a GHG emission penalty cost of \$13/tonne, scenario 7 shows a COE of \$0.36/kWh. The small difference in the calculated COE (COE for scenario 6 was \$0.36/kWh) indicates, scenario 7 could be replaced by a hybrid system reasonably. The results of this study were compared with the numbers reported in the literature. Kusakana [10] found a pure diesel system to be significantly more expensive than a variety of renewable systems which is not in line with the results obtained in this study. Different data sources and resource availability (i.e. wind speed, solar radiation, diesel price), interest rate, inflation rate are the reasons for variation between the results obtained in different studies. Kusakana et al. used much higher operation and maintenance cost for the diesel generator and cost of diesel which led to increase cost of energy (COE) compared to this study. The COE found in this study is in a good agreement with those in existing literature [7, 11, 15, 33].

This study could play a vital role in decision making towards sustainability. Greenhouse gas emission is a big environmental concern. The selection of a hybrid renewable energy system does not only depend on the low net present cost (NPC) and cost of energy (COE) but also on the GHG emissions. It is the decision of the policy makers and stockholders to choose the system which is optimum considering the cost and emissions. When the renewable fraction is increased, COE is increased but GHG emissions are decreased. 80% renewable scenario can satisfy the demand with 72% higher COE but 83% lower CO_2 emissions compared to the diesel-battery scenario. Sensitivity analyses were conducted in this study to analyze the impacts of different parameters (i.e., diesel price, solar radiation, wind speed, and discount rate) on the cost of the hybrid system. Diesel price was found to be the dominating parameter among these four parameters. It was also found that with a lower diesel price, higher wind speed, and a lower discount rate hybrid options become more attractive with lower COEs.

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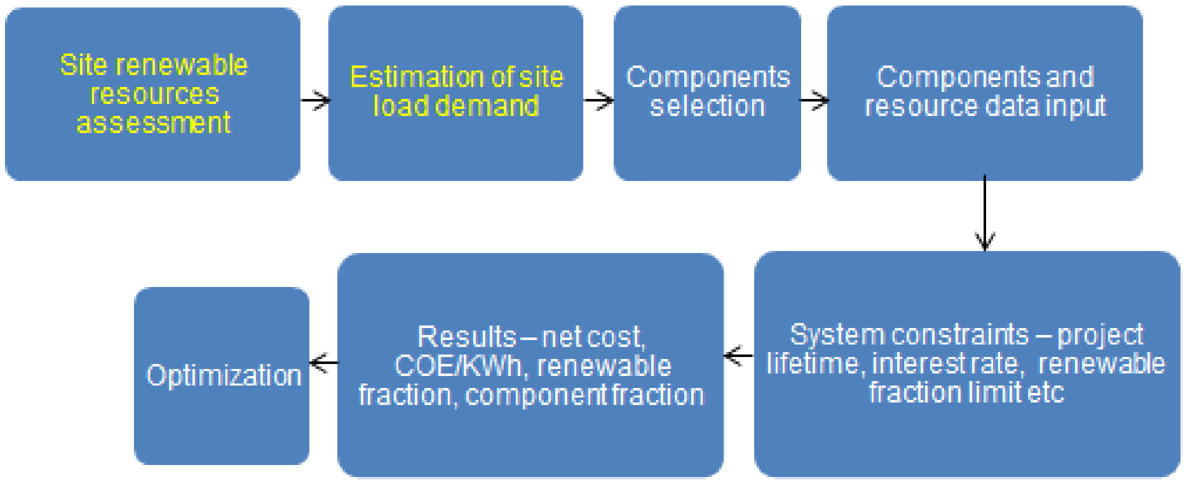


Figure 1: Detailed steps of the analysis in this study

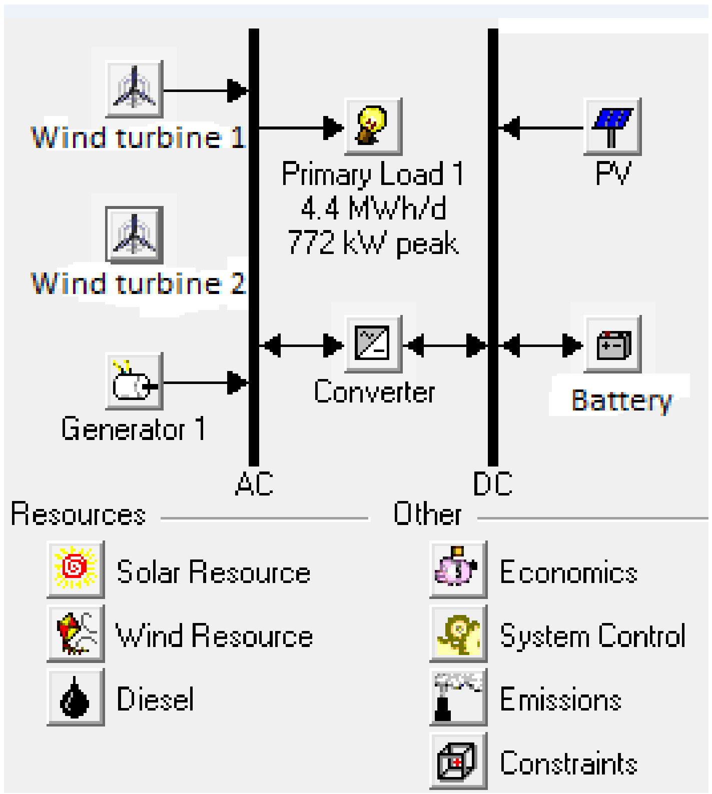


Figure 2: Hybrid energy system

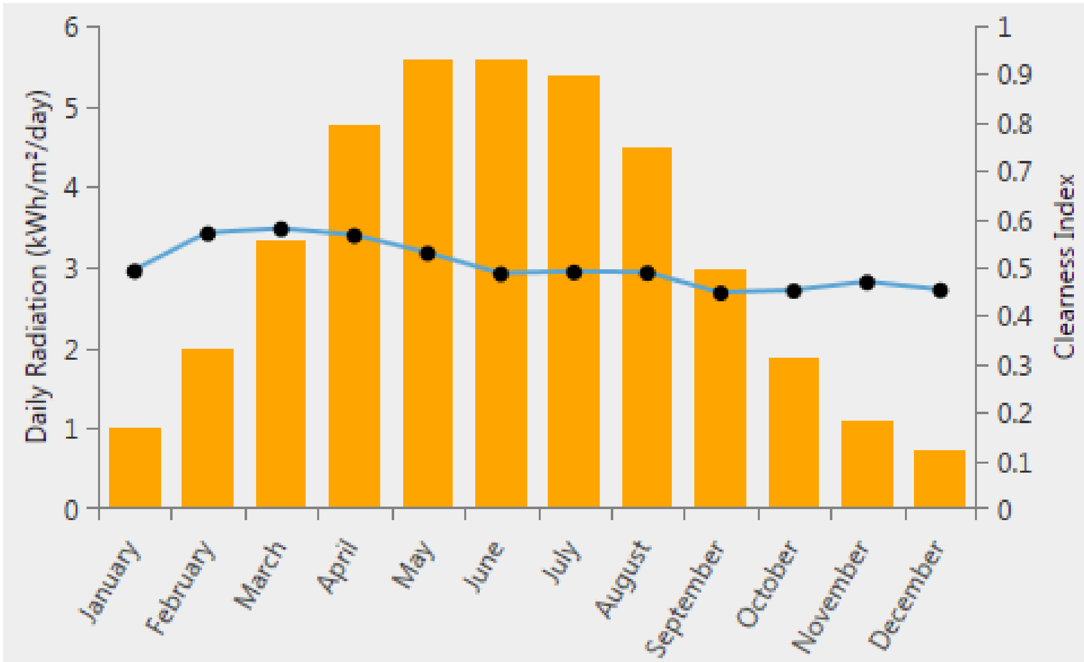


Figure 3: Monthly solar radiation and clearness index at Sandy Lake (generated by HOMER, using data from [19])

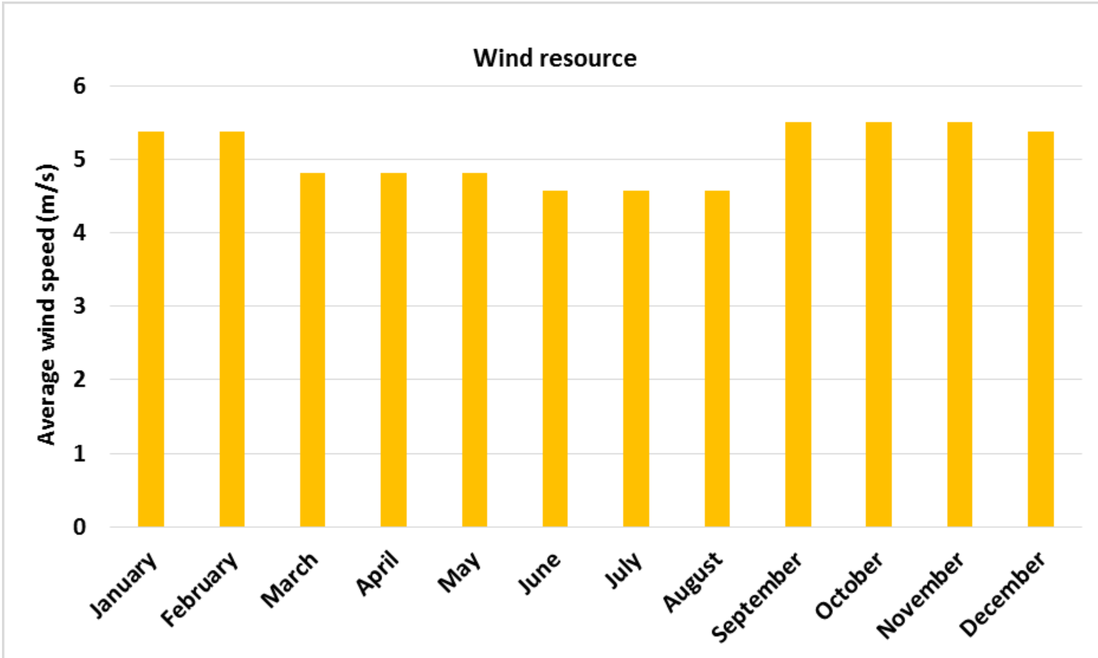
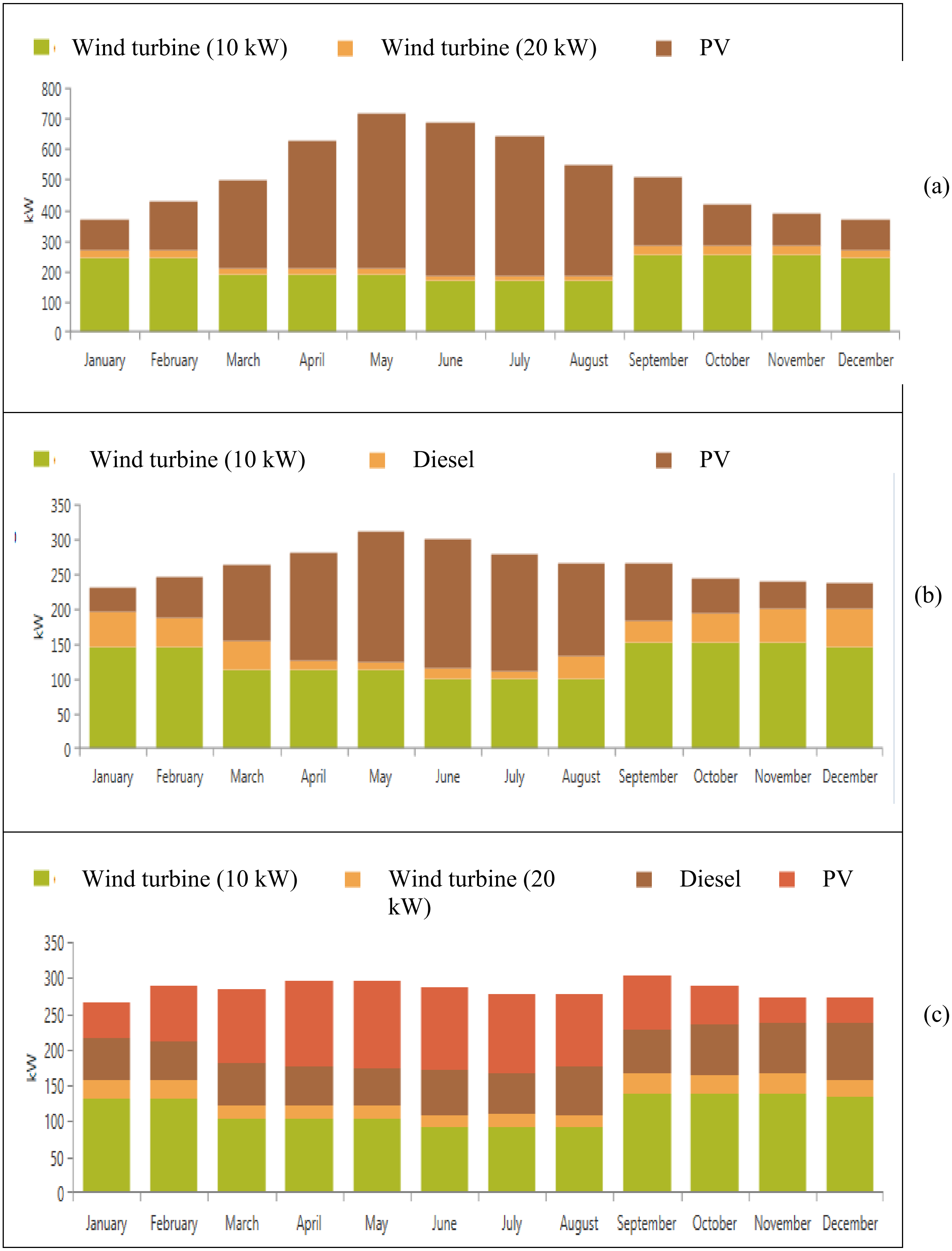


Figure 4: Wind speed variation throughout the year at Sandy Lake



Wind turbine (10 kW)
Wind turbine (20 kW)
PV
kW
0
100
200
300
400
500
600
700
800
January
February
March
April
May
June
July
August
September
October
November
December
(a)
Wind turbine (10 kW)
Diesel
PV
kW
0
50
100
150
200
250
300
350
January
February
March
April
May
June
July
August
September
October
November
December
(b)
Wind turbine (10 kW)
Wind turbine (20 kW)
Diesel
PV
kW
0
50
100
150
200
250
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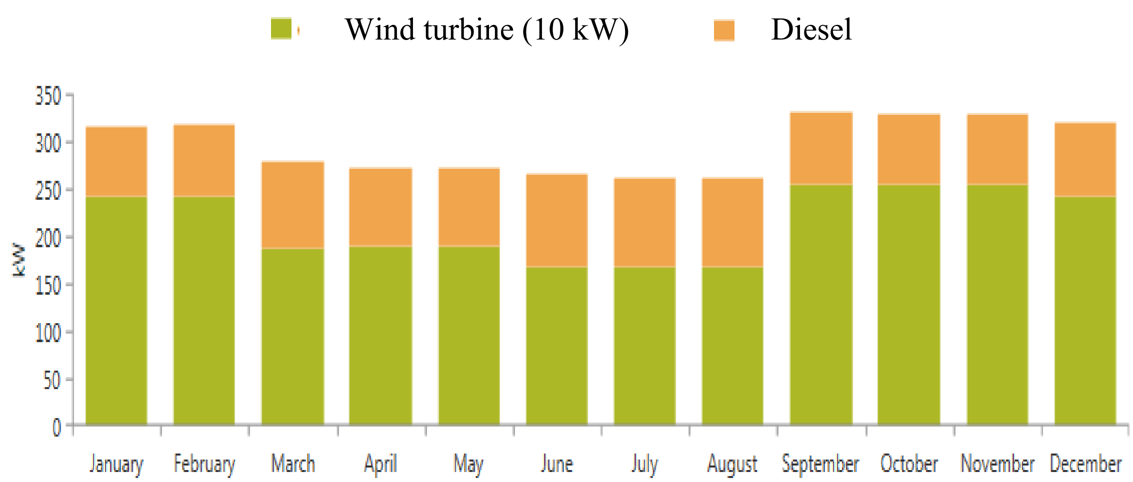
350
January
February
March
April
May
June
July
August
September
October
November
December
(c)


Wind turbine (10 kW)
Diesel
kW
350
300
250
200
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100
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0
January
February
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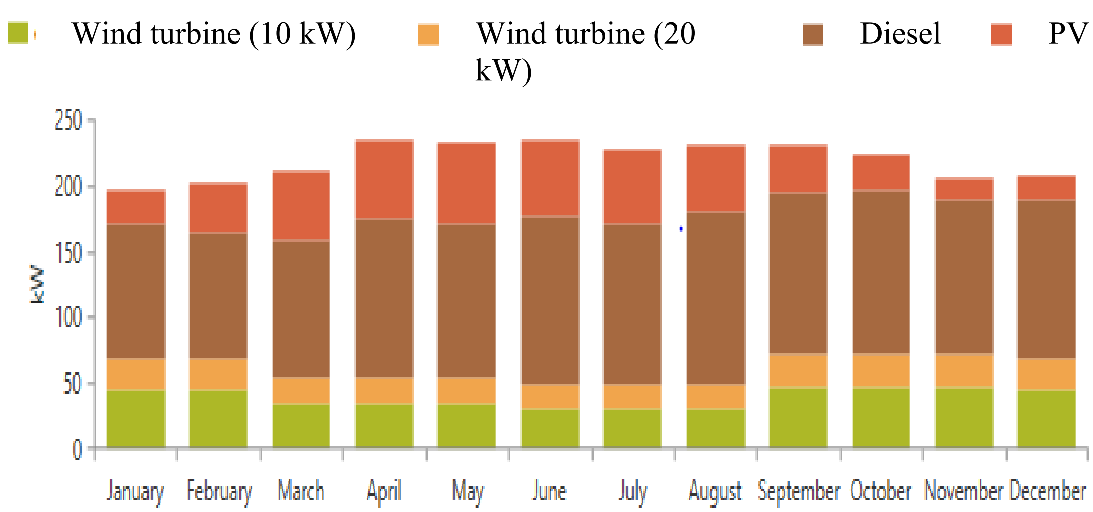
September
October
November
December

(d)


Wind turbine (10 kW)
Wind turbine (20 kW)
Diesel
PV
kW
250
200
150
100
50
0
January
February
March
April
May
June
July
August
September
October
November
December

(e)

(f)

(g)

Figure 5: Monthly electricity generation for different scenarios. (a) 100% renewable resources; (b) 80% renewable resources; (c) 65% renewable resources; (d) 50% renewable resources; (e) 35% renewable resources; (f) 21% renewable resources; (g) battery-diesel generator (0% renewable resources)

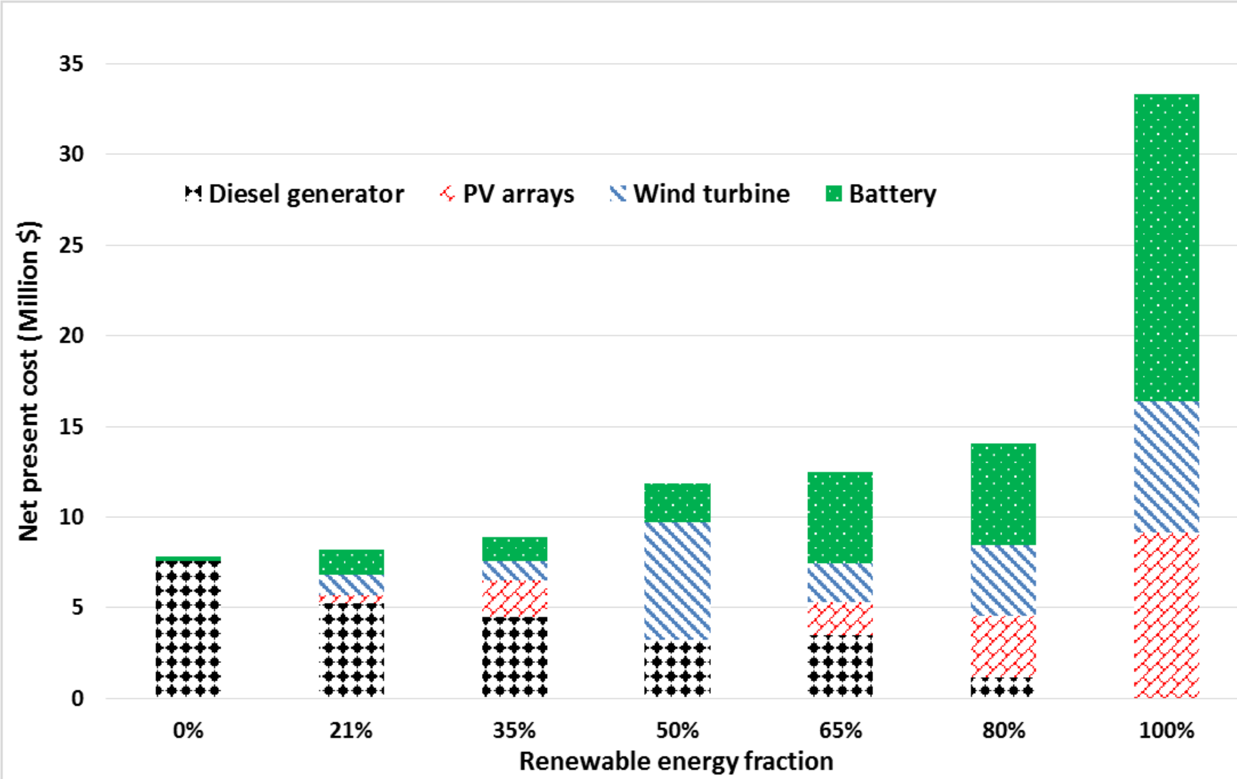


Figure 6: Net present cost of components for different scenarios

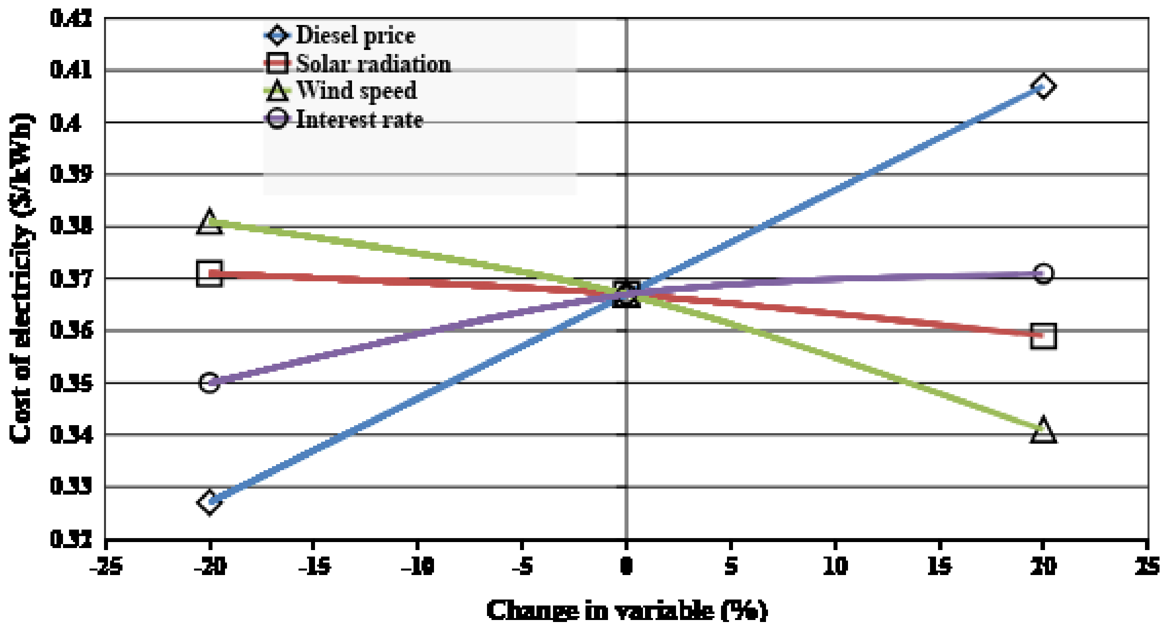


Figure 7: Sensitivity analysis for the 21% renewable resources scenario

Table 1: Comparison of resource availability at different regions around the globe

Region	Solar insolation (kWh/m^2/day)	Wind speed (m/s)
Sandy Lake, Canada (This study)	3.24	5.06
Khavar-E-Bala, Iran	5.33	6.49
Jos, Nigeria	6.00	3.46
Palari, India	4.99	3.50
Gold Coast Seaway, Australia	4.73	5.46
Ras Musherib, UAE	5.65	4.75
Rawdat Ben Habbas, Saudi Arabia	5.48	5.14
Adafoah, Ghana	4.93	3.67
St. Martin's Island, Bangladesh	4.79	4.85
Place near Stuttgart, Germany	3.14	5.17
Catalina Island, California, USA	5.20	5.34

All the data for solar insolation and wind speed were taken from NASA Surface Meteorology and Solar Energy database [19].

Table 2: Cost parameters used for different components of a hybrid system

Components	Capital cost	Replacement cost	Maintenance cost	References
Solar PV	$3,570/kW	$3,570/kW	$25.5/kW/yr	[22]
Wind turbine	$4,500/kW	70% of capital cost	2% of capital cost	[23]
Diesel generator	$34,647/unit	$34,647/unit	$0.01/hr	[24, 11]
Battery	$1122/unit	$1000/unit	$10.2/unit/yr	[1]
Converter	$700/kW	$700/kW	$10/kW/yr	[10]

Table 3: Component combinations for the seven scenarios considered in this study

Components	100% renewable	80% renewable	65% renewable	50% renewable	35% renewable	21% renewab
PV	1900 kW	700 kW	400 kW	-	200 kW	100 kW
Wind turbine (10 kW)	100 units	60 units	30 units	100 units	10 units	15 units
Wind turbine (20 kW)	6 units	-	10 units	-	10 units	1 unit
Diesel generator	-	480 kW	480 kW	480 kW	640 kW	640 kW
Battery (83 Ah each)	600 strings	200 strings	200 strings	75 strings	50 strings	50 string
Converter	750 kW	600 kW	300 kW	300 kW	300 kW	200 kW

Table 4: Electricity production, excess electricity, and cost of electricity (COE) for seven scenarios

Scenario	Electricity production (MWh/year)	Production by component (%)	Excess electr generation
100% renewable resources	4.522	PV- 54.40, Wind turbine- 45.60	64.9
80% renewable resources	2.304	PV- 39.32, Wind turbine- 48.53, Diesel generator- 12.14	27.7
65% renewable resources	2.487	PV- 29.29, Wind turbine- 48.83, Diesel generator- 21.89	33.2
50% renewable resources	2.588	Wind turbine- 71.99, Diesel generator- 28.01	18.8
35% renewable resources	1.922	PV- 18.95, Wind turbine- 27.71, Diesel generator- 53.34	15.4
21% renewable resources	1.602	PV- 13.85, Wind turbine- 26.51, Diesel generator- 59.64	3.8
Diesel-battery	1.640	Diesel generator- 100	10.7

Table 5: Diesel properties [17]

Property	Value
Low heating value	43.3 MJ/kg
Density	820 kg/m^3
Carbon content	88%
Sulfur content	0.33%

Table 6: Emissions analysis for different scenarios*

Scenarios	CO_2	CO	Unburned hydrocarbons	Particulate matter	SO_2	NOx
100% renewable	0	0	0	0	0	0
80% renewable	204	0.50	0.06	0.04	0.41	4.5
65% renewable	413	1.01	0.12	0.07	0.83	9.01
50% renewable	540	1.33	0.14	0.10	1.08	11.90
35% renewable	786	1.94	0.21	0.15	1.58	17.31
21% renewable	857	2.12	0.23	0.16	1.72	18.87
Battery-diesel generator	1,232	3.04	0.33	.229	2.47	27.14

***All the emissions are in the unit of tonnes/year**

Table 7: Cost of electricity (COE) after carbon tax addition for different scenarios

Scenarios	COE with emission penalty ($/kWh)
100% renewable resources	1.48
80% renewable resources	0.62
65% renewable resources	0.54
50% renewable resources	0.42
35% renewable resources	0.39
21% renewable resources	0.37
Battery-diesel generator	0.36

Table 8: Sensitivity analysis to check the cost of electricity (COE) of the system

Diesel price / CO_2 penalty	0.50	0.70	0.90	1.10	1.30
3	0.26	0.31	0.36	0.40	0.44
13	0.27	0.32	0.37	0.41	0.45
23	0.28	0.33	0.37	0.41	0.45
35	0.29	0.33	0.38	0.42	0.45
50	0.29	0.34	0.39	0.43	0.46

Table 9: Sensitivity analysis to check the renewable fraction of the system

Diesel price / CO_2 penalty	0.50	0.70	0.90	1.10	1.30

3	5	15	21	30	45
13	5	15	21	30	45
23	5	15	21	30	45
35	15	21	30	45	53
50	15	21	30	45	53