Cost Analysis of an Optimized Hybrid Energy System for a Remote Area in St. John’s, NL

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Abstract — **In the current energy field scenario, hybrid energy, combining both conventional and non-conventional energy, plays a significant role. With the development of technology, this new energy category has gained popularity due to its efficiency and cost-effectiveness, especially in remote places where the primary grid is located far away. This research puts forth an optimum design of a PV-diesel hybrid energy system for analysis of a remote off-grid power system in St. John's, Newfoundland, Canada, using HOMER (Hybrid Optimization Model for Electric Renewables) software. The study involves connecting a diesel generator and a PV solar panel to the bus. To ensure uninterrupted load distribution, batteries are combined as storage. A technical and economic study of the hybrid energy system is conducted by simulation through HOMER. The levelized energy cost is expected to be lower under the proposed arrangement.**

Index Terms: **hybrid energy, HOMER, COE, energy production, fuel consumption.**

I. Introduction

Because St. John’s has long relied on diesel generators to generate electricity, many residents feel excluded from upcoming developments. Furthermore, the high amount of fuel burnt has led to greenhouse gas emissions harming the environment and the health of the locals. Fossil fuel prices rise, therefore, renewable energy is necessary to produce the electrical supply. The increasing use of renewable energy connected to the grid poses considerable challenges because of its erratic power delivery. If we want to ensure a constant supply of electricity to the system, we must discover better techniques to store energy. Due to its capacity to store energy and the potential for energy transportation, solar energy is the ultimate energy source. Since a few years ago, shifting to Renewable Energy System (RES) has been necessary to meet the world’s energy needs because of rising environmental concerns caused by the depletion of fossil fuels. The deployment of RES in the commercial, industrial, and residential sectors has been drawn by its eco-friendliness, scalability, and other significant qualities. The power system’s operation and control are now more unpredictable due to the ongoing trend of integrating RES. Additional resources are needed to sustain RES because of its sensitivity to unpredictable weather conditions. Energy Storage Systems (ESS) are a need in this situation as one of the many resources to assist RES penetration. The capacity of ESS, however, is constrained in terms of meeting all application needs. Therefore, a possible approach is the hybridization of several ESS to create a composite ESS. Power sharing control is essential to use the complementing qualities of each ESS while integrating them. The notable challenges faced during the integration of RES are voltage instability, load discrepancy, frequency fluctuation, poor power quality, and load-following [1]. A possible way to get around these restrictions and enable the grid to run steadily is to incorporate ESS. By integrating ESS and RES into the microgrid, power fluctuations can be avoided, power quality can be improved, frequency regulation can be enhanced, and more ancillary services may be available [2]. ESS plays a significant role in the advancement of electric energy systems and extends RES to remote power locations around the globe [3–6]. Renewable energy power generators require high initial investments and relatively low operating costs. The most important costs are generated by the battery park and then come the photovoltaic panels. The hybrid PV/wind/diesel/hydropower system is profitable if the distance from the village to the transformer station is greater than 1.90 km [7]. In many cases, hybrid energy systems have been shown to drastically lower the overall lifespan cost of stand-alone power supplies while also supplying a more dependable source of electricity thanks to the mix of energy sources [8–10].

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II. Methodology

A. Description of Proposed Hybrid Energy System

Hybrid Energy: Hybrid energy combines different power and energy systems. A standard hybrid power system combines nonconventional energy, e.g., solar energy, wind energy, hydro energy, etc., with another energy source, such as diesel energy, fuel cell, battery storage system, etc., to meet the required load demand.

Photovoltaics: Photovoltaics (PV) convert light into electricity using semiconducting materials exhibiting photovoltaic effects. PV is famous for generating electricity commercially with no pollution. Solar modules of many solar cells are used in a photovoltaic system to produce electricity. PV installations can be floating, wall-mounted, rooftop-mounted, or ground-mounted.

Diesel Generator: Diesel generator combines a diesel engine with an electric generator to generate electrical energy. Diesel generating sets are used in places without connection to a power grid or as an emergency power supply if the grid fails, as well as for more complex applications such as peak-lopping, grid support, and export to the power grid.

Converter: An electrical or electromechanical device for converting electrical energy is called a power converter. A power converter can adjust the voltage or frequency of the current, convert alternating current (AC) into direct current (DC), or do any combination of these things. A power converter could be as straightforward as a transformer or incredibly sophisticated, as a resonant converter. The term can also be used to describe a group of electrical devices that change the frequency of an alternating current. Voltage regulation and redundant components are frequently used in power conversion systems.

Storage: Energy storage is the process of storing energy produced at one moment for use at a later period in order to balance out the imbalance between energy production and demand. An accumulator or battery is a term used to describe a device that stores energy. There are several different types of energy, including kinetic, latent heat, gravitational potential, chemical, electricity, and radiation. Energy storage is the process of transforming energy from forms that are challenging to store to forms that are easier or more practical to store.

B. Description of Designing Tool

HOMER (Hybrid Optimization Model for Electric Renewables) is a specialized tool for microgrid electrical

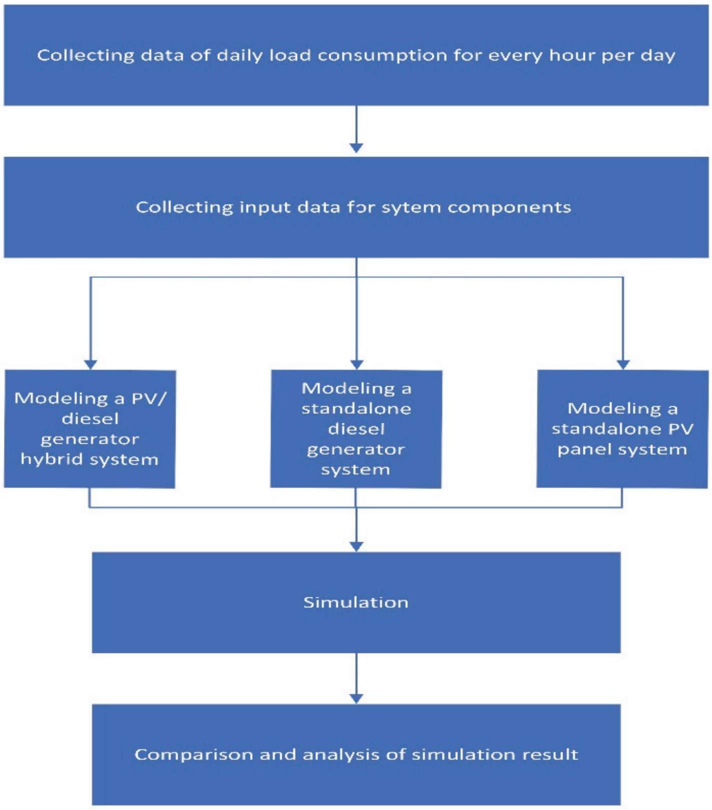

Fig. 1. Research methodology flowchart.

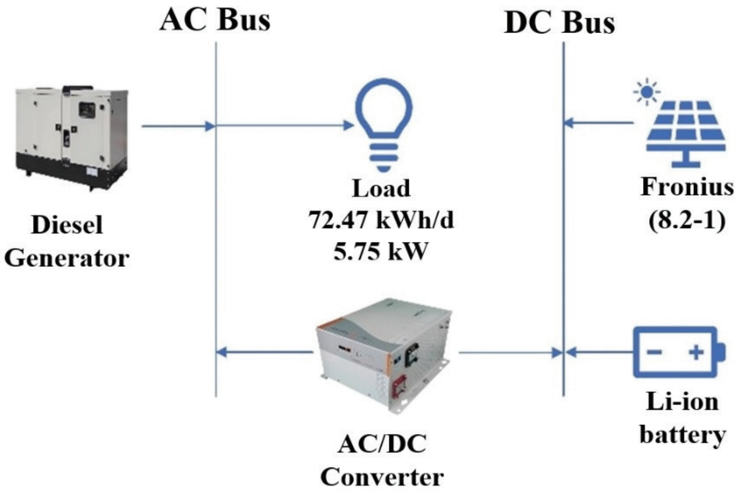

Fig. 2. Schematic diagram.

TABLE 1. Load Profile of January

Hour	Load (kWh)
0	3.4
1	3.3
2	3.3
3	3.2
4	3.1
5	3.1
6	3
7	3
8	2.93
9	2.88
10	2.83
11	2.8
12	2.77
13	2.74
14	2.73
15	2.68
16	2.63
17	2.6
18	2.58
19	3.2
20	3.3
21	3.4
22	3.5
23	3.5

power systems' design, modeling, optimization, and sensitivity analysis. HOMER navigates the complexities of building cost-effective and reliable hybrid microgrid and grid-connected systems that combine traditionally generated and renewable power, storage, and load management. This program was used to study and design hybrid energy systems utilizing both renewable and nonrenewable energy sources.

C. Step-by-Step Process

To conduct this study, we first demonstrated a load profile for a house in St. John's, NL, with a 72.47 kWh/day and peak load of 5.75 kW in 24 hours for the month of January as January is the month when the electricity consumption is the highest in this region. After setting up the load profile, all the data for the equipment and machinery were obtained to connect with the load. After connecting the whole set up, three simulations were executed based on three different scenarios. One with the proposed hybrid model where the load is connected to the PV panel, diesel genset, and Li battery, one with the standalone diesel genset, which is considered as the base case, and the third simulation was with the standalone PV panel. The numerical results of all these simulations were analyzed and compared to obtain the best possible case with the lower Cost of Energy (COE). After the analysis, the case of standalone PV panel was eliminated as the generation of electricity was minimum.

D. Schematic Diagram

In the proposed system, a PV panel is connected to the load through a DC bus, and the conventional source, i.e., the diesel genset, is connected to the load through an AC bus. For storage and power backup purpose, a Li battery is connected to the DC bus. To convert alternating current to direct current and vice versa, a converter is also connected to the whole system. Upon gathering all the necessary data through HOMER, relevant graphs and results are generated and then used to analyze the expected result.

A load consumes energy from the microgrid. A primary load can model anything that uses electricity, such as a light bulb or a motor. Primary load is the electrical load that the system must meet immediately in order to avoid unmet load. At first, the load profile of the peak month (January) of St. John's was set up using the average hourly energy consumption of 3 kW [11].

After setting up the load profile, the data of solar Global Horizontal Irradiance (GHI) was required, which was obtained from HOMER through NASA Prediction of

Fig. 3. Solar GHI data.

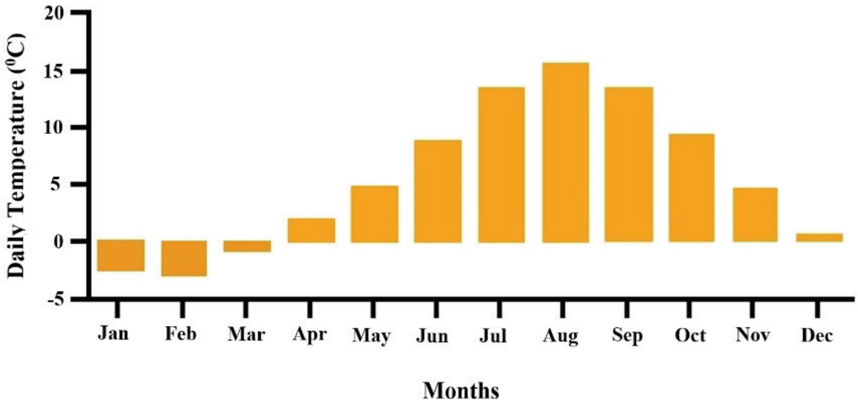

Fig. 4. Monthly average temperature.

TABLE 2. Specification of Converter

Description	Specification
Capacity	1 kW
Capital cost	300 $
O&M cost	60 $
Lifetime	15 years

TABLE 5. Specification of Generator

Description	Specification
Fuel	Diesel
Capital cost	500 $
O&M cost/hr	0.03 $
Lifetime	90 000 hrs
Minimum load ratio	30

TABLE 3. Specification of PV

Description	Specification
Capacity	8.25 kW
Capital cost	3 000 $
O&M cost	10 $
Lifetime	25 years

TABLE 6. Cost Summar

Description	Base Case ($)	Ы
Initial Capital	3 200	47 158
O&M	27 652/yr	18 005/yr
COE	1.05/kWh	0.819/kWh

TABLE 4. Specification of Storage

Description	Specification
Capacity	1 kW
Nominal voltage	6 V
Capital cost	550 $
O&M cost	10 $
Lifetime	15 years

TABLE 7. Economic Metrics

Description	Specification
IRR	23%
ROI	17.9%
Simple payback	4.1 years
Minimum load ratio	30

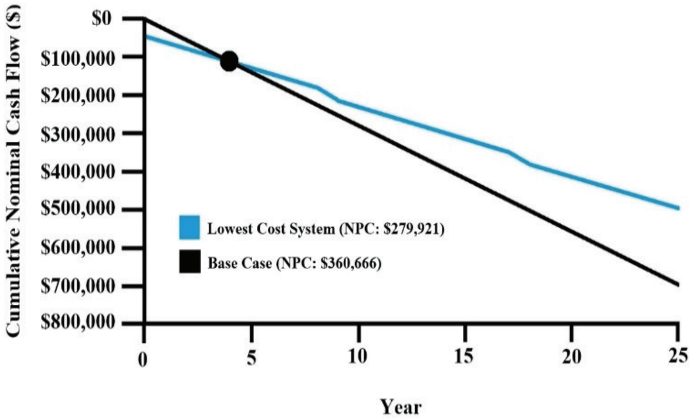

Fig. 5. Hybrid system project break-even graph.

Worldwide Energy Resource (POWER) database. GHI is the total solar radiation incident on a horizontal surface. It is the sum of Direct Normal Irradiance (DNI), Diffuse Horizontal Irradiance, and ground-reflected radiation. HOMER uses Solar GHI to compute flat-panel PV output. Solar GHI resource is used to calculate flat panel PV array output.

In addition, the monthly average temperature data was required, which was obtained from HOMER through NASA Surface Meteorology and Solar Energy database.

E. Specifications of Components

Converter: A generic 1 kW converter was selected as PV panel for the intended system. The specification (from HOMER) of the converter is given below.

PV: Fronius Primo 8.2-1 PV panel was selected for the intended system. The specification (from HOMER) of the PV is given below.

Storage: A 1kWh Li-Ion battery was selected as the storage for the intended system. The specification (from HOMER) of the storage is given below.

Generator: An auto-genset was selected as the fuel generator for the intended system. The specification of the generator is given below.

F. Numerical Analysis

The Project lifetime is the length of time over which the costs of the system occur. HOMER uses the project lifetime to calculate annualized costs from net present costs. HOMER assumes that salvage values occur at the end of the project lifetime. In this proposed project, the project lifetime is 25 years. The simple payback period at the point where the lower cost system case and the base case intersect each other in the project lifetime curve is 4.1 years.

The initial capital cost of a component is the total installed cost of that component at the beginning of the project. The Operation and Maintenance (O&M) cost of a component is the cost associated with operating and maintaining that component. The total O&M cost of the system is the sum of the O&M costs of each system component. The annualized cost of producing electricity (i.e., the total annualized cost less the cost of supplying the thermal load) is divided by the total electric load provided by HOMER to determine the COE:

$$COE = \frac{C_{ann,tot} - C_{boiler} H_{served}}{E_{served}}, \quad (1)$$

where $C_{ann,tot}$ – total annualized cost of the system [$/yr]; C_{boiler} – boiler marginal cost [$/kWh]; H_{served} – total thermal load served [kWh/yr]; E_{served} – total electrical load served [kWh/yr].

The Return on Investment (ROI) is the yearly cost savings relative to the initial investment. HOMER calculates the return on investment with the following equation:

$$ROI = \frac{\sum_{i=0}^{R_{proj}} C_{i,ref} - C_i}{R_{proj}\left(C_{cap} - C_{cap,ref}\right)}, \quad (2)$$

where, $C_{i,ref}$ – nominal annual cash flow for base (reference) system; C_i – nominal annual cash flow for current system; R_{proj} – project lifetime in years; C_{cap} – capital cost of the current system; $C_{cap,ref}$ – capital cost of the base (reference) system.

The ROI is the average yearly difference in nominal cash flows over the project lifetime divided by the difference in capital cost.

Internal Rate of Return (IRR) is the discount rate at which the base case and current system have the same net present cost. HOMER calculates the IRR by determining the discount rate that makes the present value of the difference of the two cash flow sequences equal to zero. The Return on Investment (ROI) is the yearly cost savings relative to the initial investment. The ROI is the average yearly difference in nominal cash flows over the project lifetime divided by the difference in capital cost. Simple payback is the number of years at which the cumulative cash flow of the difference between the current system and base case system switches from negative to positive. The

Table 8. Comparative Economics of Hybrid System

Metric	Value
Present worth ($)	80 745
Annual worth ($/yr)	6 246
ROI (%)	17.9
Internal rate of return (%)	23
Simple payback (yr)	4.07
Discount payback	4.79

Table 9. Fuel Consumption for Hybrid System

Description	Value	Units
Total fuel consumed	3 179	l
Average fuel per day	8.71	l/day
Average fuel per hour	0.363	l/hr

Table 10. Fuel Consumption for Base Case

Description	Value	Units
Total fuel consumed	9 412	l
Average fuel per day	25.8	l/day
Average fuel per hour	1.07	l/hr

Table 11. Emissions from Base case

Description	Value	Units
Carbon dioxide	24 637	kg/yr
Carbon monoxide	155	kg/yr
Unburned hydrocarbons	6.78	kg/yr
Particulate matter	0.941	kg/yr
Sulfur dioxide	60.3	kg/yr
Nitrogen oxides	146	kg/yr

Table 12. Emissions from Hybrid System

Description	Value	Units
Carbon dioxide	8 321	kg/yr
Carbon monoxide	52.5	kg/yr
Unburned hydrocarbons	2.29	kg/yr
Particulate matter	0.318	kg/yr
Sulfur dioxide	20.40	kg/yr
Nitrogen oxides	49.3	kg/yr

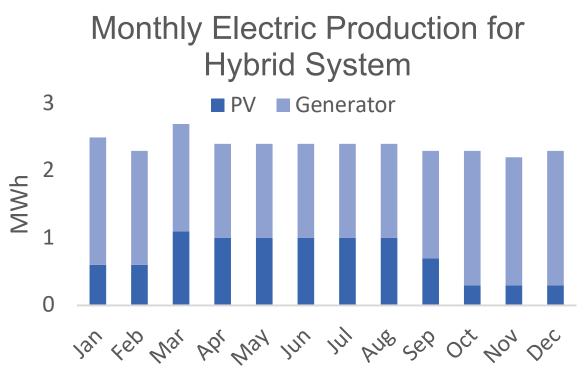

Fig. 6. Monthly electric production for the hybrid system.

payback indicates how long it would take to recover the difference in investment costs between the current system and the base case system.

The present worth is the difference between the net present costs of the base case system and the current system. The sign of the present worth indicates whether the current system compares favorably as an investment option with the base case system: A positive value indicates that the current system saves money over the project lifetime compared to the base case system. The present value is the current equivalent value of a set of future cash flows, taking into account the time value of money. The Annual worth is the present worth multiplied by the capital recovery factor. The total annualized cost is the annualized value of the total net present cost. HOMER calculates the total annualized cost using the following equation:

$$C_{ann,tot} = CFR\,(i,\, R_{proj}{\cdot}C_{NPC,tot}), \qquad (3)$$

where CFR () – a function returning the capital recovery factor; $C_{NPC,tot}$ – the total net present cost [$]; i – the annual real discount rate [%]; R_{proj} – the project lifetime [yr].

Payback is the number of years at which the cumulative cash flow of the difference between the current system and base case system switches from negative to positive. The payback is an indication of how long it would take to recover the difference in investment costs between the current system and the base case system. The Simple payback is where the nominal cash flow difference line crosses zero. The Discounted payback is where the discounted cash flow difference line crosses zero.

The total electrical production is the total amount of electrical energy produced by the power system in one year. It is the sum of the electrical energy produced by all components of the system. From the simulation, it is obtained that for a standalone diesel generator, the generation of electricity from the generator is 26 606 kWh/yr. The amount of excess electricity generated is 0.582%, i.e., 155 kWh/yr.

The specific fuel consumption is the average amount of fuel consumed by the generator per kWh of electricity it generates. HOMER calculates the specific fuel consumption using the following equation:

$$F_{spec} = \frac{F_{tot}}{E_{gen}}, \qquad (4)$$

where F_{tot} – total annual generator fuel consumption [l/yr, m^3/yr, or kg/yr]; E_{gen} – total annual electrical production of the generator [kWh/yr].

Table 9 and Table 10 indicate the fuel consumption data for both the base case and the proposed hybrid system.

HOMER calculates the emission factor (kg of pollutant emitted per unit of fuel consumed) for each pollutant prior to modelling the power system. After the simulation, it multiplies the emission factor by the value of total annual fuel used to determine the pollutant's annual emissions. HOMER employs three principal assumptions to calculate

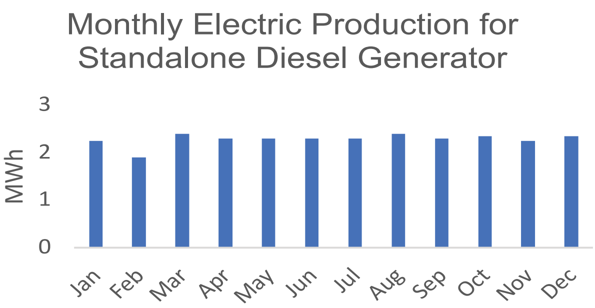

Fig. 7. Monthly electric production for standalone diesel generator.

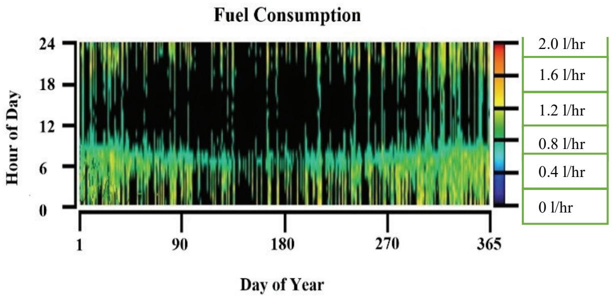

Fig. 8. Fuel consumption for hybrid system.

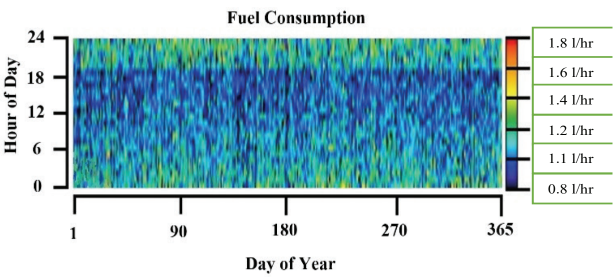

Fig. 9. Fuel consumption for base case.

emission factors of carbon dioxide and sulfur dioxide.

1. Any carbon in the fuel, which is not emitted as carbon monoxide or unburned hydrocarbons, is emitted as carbon dioxide.
2. The carbon fraction of the unburned hydrocarbon emissions is the same as that of the fuel.
3. Any sulfur in the burned fuel, which is not emitted as particulate matter, is emitted as sulfur dioxide.

III. Results and Discussions

A. COE

Table 6 indicates that the O&M cost and the COE for the base case (a diesel generator standalone system) are 27 652$/yr and 1.05$/kWh, respectively and those for the proposed hybrid system (a PV/diesel generator system) are $18 005/yr and $0.819/kWh, respectively. The scenario where the hybrid system is a combination of PV panels, a battery bank, and a diesel generator delivers the lowest COE, according to the results of the numerous investigated scenarios.

B. Electricity Production

From the simulation of the intended hybrid system, we obtain that electricity generated from the PV is 35.3%, which is 10 681 kWh/yr, and that from the generator is 64.7%, which is 19 592 kWh/yr. The excess electricity generated is 4.35%, which is 1 318 kWh/yr.

From the simulation of a standalone diesel generator, we obtain that electricity produced from the generator is 26 606 kWh/yr. The excess electricity generated is 0.582%, which is 155 kWh/yr.

According to the outcomes of the multiple analyzed scenarios, the hybrid system that combines PV panels, a battery bank, and a diesel generator produces the most electricity.

C. Fuel Consumption

The total fuel consumption for the base case is 9 412 l, and average daily fuel consumption is 25.8 l. The same parameters for the proposed hybrid system are 3 179 l and 8.71 l, respectively, which is 66 % less than the base case.

D. Emissions

As seen in Table 11, emissions of carbon dioxide, carbon monoxide, unburned hydrocarbons, and sulfur dioxide for the standalone diesel generator are 24 637 kg/yr, 155 kg/yr, 6.78 kg/yr, and 60.3 kg/yr, respectively.

According to Table 12, for the proposed hybrid system combining PV panel and diesel generator, the emissions of carbon dioxide, carbon monoxide, unburned hydrocarbons, and sulfur dioxide are 8 321 kg/yr, 52.5 kg/yr, 2.29 kg/yr, and 20.4 kg/yr, respectively.

A comparison of both tables suggests that with the proposed hybrid system, the emissions of carbon dioxide, carbon monoxide, unburned hydrocarbons, and sulfur dioxide are on average 61% less than those of the base case with the standalone diesel generator.

IV. Conclusion

This study aims to electrify outlying areas in St. John's, Newfoundland and Labrador, with a hybrid system that combines solar energy with a diesel generator, and a battery bank. Different situations have been examined to determine the best configuration that achieves the lowest cost of electricity production. This study and optimization employed HOMER software. The results obtained suggest that the optimum scenario, which yields the lowest COE, is the one that combines PV panels, a diesel generator, and battery units. The hybrid system's COE is $0.819/kWh. Because of the low use of diesel fuel, carbon dioxide emissions are regarded as low. Two other situations were also examined. The COE for the standalone diesel generator was $1.05/kWh. However, implementing such hybrid systems might be more acceptable when taking into account off-grid regions and addressing environmental considerations. In conclusion, the hybrid PV/diesel generator system has a lot of promise for application in electrifying remote off-grid areas. These hybrid renewable energy systems benefit the environment by using less diesel and emitting less carbon dioxide. Although the analysis in this study was done for a location in St. John's, the findings can be applied to any region with about the same characteristics.

V. Nomenclature

$C_{ann,tot}$ – total annualized cost of the system [\$/yr];
C_{boiler} – boiler marginal cost [\$/kWh];
H_{served} – total thermal load served [kWh/yr];
E_{served} – total electrical load served [kWh/yr];
$C_{i,ref}$ – nominal annual cash flow for base (reference) system;
C_i – nominal annual cash flow for current system;
R_{proj} – project lifetime [yr];
C_{cap} – capital cost of the current system;
$C_{cap,ref}$ – capital cost of the base (reference) system;
CFR () – a function returning the capital recovery factor;
$C_{NPC,tot}$ – the total net present cost [\$];
i – the annual real discount rate [%];
R_{proj} – the project lifetime [yr];
F_{tot} – total annual generator fuel consumption [l/yr, m^3/yr, or kg/yr];
E_{gen} – total annual electrical production of the generator [kWh/yr].

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