The Effect of Fuel Price on Off-grid Renewable Energy Systems

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Abstract

Carbon emissions mitigation is driving the need to decarbonize different energy systems. Alongside the energy systems decarbonization, there is uncertainty over determining the best goals in terms of cost and emissions. In this work, a hybrid energy system which consists of renewable energy systems, storage systems and a diesel generator are considered to supply the energy demands of an off-grid house. One of the main challenges in off-grid systems is the trade-offs between energy storage and importing diesel. This challenge is due to the variability of both renewable energy resources and the building demands. This paper introduces an energy hub model that is used for the optimal sizing and operation of an energy system. Four scenarios are considered to decide how well an off-grid system works in term of its total cost and greenhouse gas emissions.

Our results show that hybrid systems are 35% cheaper (over a 25 year lifespan) than the base case using a diesel generator. This situation gets worse at higher diesel prices, and is helped by lower PV and battery prices, but not in a linear manner. This is illustrated using contour plots that show the impact of different combinations of variables.

Introduction

There are over 280 remote communities in Canada which use diesel generators to meet electricity demand (Royer, 2011; Canada, 2018). Use of diesel fuel is expensive and has large carbon dioxide emissions. Moreover, the total energy cost is not just dependant on fuel cost. It is also affected by generator size and efficiency and the cost of other utilities to produce power all time (Royer, 2011). Moreover, fuel prices are highly dependent on type of transportation to site (Royer, 2011). We considered prices between \$1/L and \$5/L to account for the very high cost of transport to very remote locations.

Integration of renewable energy sources into these systems is a possible solution to reduce carbon emissions and decrease electricity costs due to lower

diesel consumption. As a result of renewable energy resource variability, combination of various renewable energy technologies increase the reliability of the energy system, lower GHG emissions and may reduce costs.

In recent years, a lot of research on off-grid hybrid energy systems have been published. The various studies differ by climate conditions, input data, technologies and modelling framework. An economic and technical simulation of a hybrid energy system including a wind turbine, photovoltaic panels and diesel backup for residential demand in remote areas is studied by Saheb-Koussa et al. (2009). The simulation in this study results indicate that the hybrid system provides higher system performance and reliability than photovoltaic or wind alone. In 2012, Asrari et al. (2012) studied different combinations of wind turbine, photovoltaic panels, battery and diesel generator for a remote rural village in Iran. A techno-economic model of hybrid energy storage technologies for a solar-wind generation system is evaluated in Ren et al. (2013). A multi-objective optimization problem to minimize cost and life cycle emissions of an off-grid PV-wind-diesel-battery storage has been done (Dufo-López et al. (2011)). The results in this study show high life cycle emissions from PV panels, batteries, and wind turbines leads hybrid energy systems to include a diesel generator in order to reduce cost and emissions even if the diesel generator only runs few hours in the year.

There are various methods and tools that are used in existing studies. A review of different approaches for the optimum design of hybrid renewable energy systems is presented in Erdinc and Uzunoglu (2012). Sinha and Chandel (2014) presents a review of software tools for hybrid renewable energy systems. In Madziga et al. (2018), an optimization for system operation based on energy demand supply, system cost and emissions is done with the HOMER software program. Furthermore, Ngan and Tan (2012); Amutha and Rajini (2015); Abdilahi et al. (2014) have used HOMER. Discrete Harmony Search, used

for optimal sizing of an off-grid hybrid energy system for electrification of a remote area in Iran, is presented by Maleki and Askarzadeh (2014). The results of this study are compared with the discrete simulated annealing (DSA) algorithm.

Hot water tanks are often not considered in off-grid energy systems since these studies focus on electrical demand only, however they are considered in different publications about on-grid energy systems. The performance of a battery and hot water tank for on-grid systems is compared in Parra et al. (2016) for the UK. The results show integrating PV panels with a hot water tank is the most advantageous economic solution. In Casaleiro et al. (2018), a comparison of different single household system configurations with a focus on hot water demand is proposed. The results in this study highlight integrating electrified hot water systems with photovoltaic system can enhance PV self-consumption and achieve lower costs.

The results of Ngan and Tan (2012) show that hybrid systems are not the most economical in comparison with diesel only systems, however the CO_2 emissions are reduced in hybrid systems by 34%. The economic results in Saheb-Koussa et al. (2009) show that PV systems are more competitive solution in comparison with hybrid systems.

In this paper, a hybrid energy system including PV, battery, heat pump, hot water tank and diesel generator is defined to supply the electrical and hot water demands of an off-grid house in Victoria, Canada. We show the importance of renewable energy technologies prices and fossil fuel costs on the optimal sizing of energy systems in off-grid communities.

Method

Energy hub model

The energy hub model was developed to manage energy flows in a single building, building complex, city or country (Geidl and Andersson, 2005). It introduces a powerful modelling framework which represents the interaction of various energy conversion and storage systems. A new formulation of the energy hub model is presented in Evins et al. (2014) which addresses operational constraints which represent plant performance. The advantage of the energy hub approach is that various optimization problems (for example energy consumption, cost, emissions etc) can be solved. Additionally, the energy hub concept can model many different energy infrastructure.

In Figure 1, the energy hub model implemented in this paper is presented. A brief description is discussed in the following sections. For a comprehensive description of the model, the reader is referred to Evins et al. (2014).

Figure 1: Energy hub model.

Energy balance

The energy hub model in this study provides electrical energy and hot water demand for a passive building in Victoria, Canada. The energy inputs are converted to energy output by means of conversion matrix C , as shown in (1). The matrix C gives the conversion efficiency between all inputs I and all outputs L . The efficiency of all the technologies assumed to be constant. Equation (1) can be rearranged to equation (2) to allocate all decision variables P in the energy hub model and to include storage into the demand and supply balance. In equation (2), θ represent energy conversion matrix in spare form (see Table 1) which has one column per decision variable P .

$$L(t) = C \times I(t) \quad (1)$$

$$L(t) = \theta \times P(t) + e_{ch}Q_{ch}(t) - e_{dis}Q_{dis}(t) \quad (2)$$

Where e_{ch} is the charging efficiency of storage system and e_{dis} is discharging efficiency of storage system.

Capacity variables

The conversion between different energy carriers represents different energy technologies in the model. Each technology has an associated efficiency, lifetime and maximum capacity which are listed in Table 1. In addition, there are limits on each conversion according to the capacity of technologies (3).

$$P^i(t) \leq P^i \leq P_{max} \quad (3)$$

Where P_{max} is the maximum capacity of each converters (Table 1). The capacity P is a decision variable of the optimization, allowing the energy technologies to be sized and $P(t)$ is the hourly flow.

Objective function

For optimizing the proposed energy system a linear function is considered, aiming for minimal equivalent annual cost (EAC), Equation (4). EAC is the annual cost of installing and operating a system over its lifetime. EAC is calculated by dividing the net

Table 1: Energy technologies characteristics.

Technology	Efficiency (%)	Lifetime (yr)	Max capacity
PV	17.7	25	Unlimited
Diesel generator	0.46	30	Unlimited
Heat pump	4.54	20	Unlimited
Battery*	0.81	15	Unlimited
Hot water tank*	0.9	25	1000 (L)

*The energy efficiency of charging and discharging are equal.

present value (NPV) by an annuity factor $A(t,r)$.

$$\min EAC = \frac{C_{Inv}}{A(t,r)} + C_{op} \quad (4)$$

With:

$$C_{Inv} = \sum_{i,j} (C_{Inv}^i P^i + C_{Inv}^j E^j) \quad (5)$$

$$C_{op} = \sum_i I^i(t) C_f^i \quad (6)$$

$$A(t,r) = \frac{1 - \frac{1}{(1+r)^t}}{r} \quad (7)$$

Where C_{Inv} is the total installation cost, made up of the price of each technology times the capacity. C_{op} is total operation cost, made up of the input energy I times the fuel cost C_f . r is the annual interest rate in percentage per year, t is the lifetime in number of the years (see Table 1). P and E are capacity of each technology which will be determined by the optimization model.

Storage

Storage systems are necessary to match supply with demand. The storage level at each time step is shown in (8).

$$E(t+1) = (1 - n_s)E(t) + Q_{ch}(t) - Q_{dis}(t) \quad (8)$$

Where $E(t)$ is the storage level at time step t , n_s is the storage loss(%), $Q_{ch}(t)$ is charging energy to storage system and $Q_{dis}(t)$ is the output energy from storage¹. The charge and discharge at each time step should be lower than the maximum charge and discharge according to technology properties (9, 10).

$$0 \leq Q_{ch}(t) \leq Q_{ch}^{max} \quad (9)$$

$$0 \leq Q_{dis}(t) \leq Q_{dis}^{max} \quad (10)$$

¹In the results, there are occasions when charging and discharging of storage happen simultaneously. This occurs during high solar radiation, when the model uses storage to waste over-produced solar energy, since the PV is not curtailable. This will have a minor influence on the results, and could be avoided by shading the PV array at times of oversupply.

Where Q_{ch} and Q_{dis} are charge and discharge at each time step and Q_{ch}^{max} and Q_{dis}^{max} are the maximum charge and discharge of each storage system.

The storage level at each time step is limited by total capacity of storage.

$$E_{min} \leq E(t) \leq E_{max} \quad (11)$$

Where E_{min} and E_{max} are the minimum and maximum level of each storage respectively. The state of charge of the storage at the last timestep of each year has to be equal to the state of charge at the first timestep of the year.

$$E(0) = E(8760) \quad (12)$$

The goal is to simulate behaviour of the storage that would occur if it is optimized for continuous identical days.

Energy scenarios

Four different scenarios are listed in Table(2). The optimization for this energy system is done based on different diesel fuel cost C_f , PV panel cost C_{PV} and battery storage system prices C_{bat} . In addition, the optimization will be done with and without hot water tank to compare the effect of thermal storage on system cost and carbon emissions. The first scenario includes only a diesel generator to represent the cost and carbon emissions of the base case house. In scenario 2 and 3 all of the technologies in Table 1 are available. In scenario 4, the energy system does not include hot water tank. In scenario 2, the battery storage system cost is the current price (Tesla, 2018) and PV panels costs are lower than the current price, at 3000 \$/kW, to 1000 \$/kw. According to Fu et al. (2017), the residential PV system cost benchmark (including module, inverter, structural and electrical components and installation) reduces by %63 from 2010 to 2018. Therefore, we assume a long-term PV system price based on PV system cost reduction in the future and also including the potential for significant government subsidies for remote communities. Scenario 3 optimizes the energy system for different battery prices (700 to 200 \$/kWh) at constant PV costs (3000, 2400 and 1800 \$/kW). The energy system model is implemented in Python².

Load and Irradiation data

Electrical demands are calculated using an EnergyPlus model with the EPW weather data for Victoria, a nearby weather station (EnergyPlus, 2018). Victoria is located 45 km from T'Souke First Nation community on the coast of Vancouver Island. The electricity load of the house is the total power consumed per day by all appliances and electronics in the household. It is assumed that the electrical

²<https://gitlab.com/energyincities/python-ehub>

Table 2: Scenarios.

Scenario		1	2	3	4
PV	Available	No	Yes	Yes	Yes
	Cost (\$/kW)	-	[1000-3000]	3000/2400/1800	[1000-3000]
Diesel generator	Available	Yes	Yes	Yes	Yes
	Fuel Cost (\$/L)	[1-5]	[1-5]	[1-5]	[1-5]
Heat pump	Available	Yes	Yes	Yes	Yes
	Cost (\$/kW)	500	500	500	500
Battery	Available	No	Yes	Yes	Yes
	Cost (\$/kWh)	-	700	[200-700]	700
Hot water tank	Available	Yes	Yes	Yes	No
	Cost (\$/kW)	Constant	Constant	Constant	-

demand is required for lighting, appliances and electronics (laptop and mobile phone). The total area of the house is 200 m². Hot water demand is calculated based on an occupancy of 3 people which is 75 litre/day per person. This is assumed to be constant at each time step, since a standard hot water tank can be used to buffer changes in hot water load to match supply. Space heating demand is ignored for this study; we assume that the house is heated using a wood stove, as is typical in most off-grid properties in Canada (Stephen et al., 2016). Figure 2 illustrates the hourly PV energy available, which was calculated using irradiance values for the roof in the EnergyPlus model.

Figure 2: Hourly profile for solar radiation in Victoria, Canada (Wh/m²).

Results

Figure 3 shows the optimization results in terms of total system cost and total carbon for various cases. The first scenario, the base case building with no hybrid system, is shown in red. The total cost changes from 477 to 2341 \$/year, proportional to the fuel cost changing from \$1/L to \$5/L. The carbon emissions are constant at 1248 kg/year since there is only a diesel generator to provide the electrical demand of the house. The hybrid cases shown are from scenario 2 and 3, and are labelled by battery price (\$200 to \$700/kW) and PV price (\$1800 to \$3000/kW).

In the second scenario, the storage system price is constant (700 \$/kWh) but PV panel cost and diesel

(a) A comparison of the optimal cost values for different cases. The base case (diesel only) is shown in red, but truncated because the cost is so high at \$5/L.

(b) A comparison of the total carbon emissions values for different cases. The base case total carbon emissions are 1248 kg/year for all fuel costs.

Figure 3: Optimal cost and total carbon emissions for various cases.

fuel price are varied (PV between \$1000 and \$3000 and diesel fuel from \$1/L to \$5/L). Figure 4 illustrates how the total cost and total carbon emissions change

(a) Total Cost (\$/year).

The color gradient shows total cost in \$/year.

(b) Total Carbon (kg/year).

The color gradient shows total carbon in kg/year.

Figure 4: Scenario 2 (Energy storage system cost is constant).

based on this. The total cost increases when the PV panel price increases, but the lines of equal cost are not linear. Total carbon emissions changes are also not linear. For a PV price of \$1000/kW, \$1/L diesel fuel price results in 200kg/year total carbon emissions, but the price has to reach \$2/L to get to 100kg/year. At the current diesel price (\$1/L), there is no change in the total cost or total carbon emissions when PV price is in the range of 2500 to 3000 \$/kW. Next battery price changes are considered to assess the effect of storage system price. The optimization is done for three different PV prices, 3000, 2400 and 1800 \$/kW. It is shown in Figure 5 that for the current diesel price, a substantial reduction in battery price to below \$400/kWh results in lower carbon emissions to below 400kg/year, and there is also a reduction in

total cost to below \$300/year. At higher diesel prices these transitions occur earlier and more dramatically.

Figure 6 and 7 show total cost and carbon emissions

(a) Total Cost (\$/year).

The color gradient shows total cost in \$/year.

(b) Total Carbon (kg/year).

The color gradient shows total carbon in kg/year.

Figure 5: Scenario 3 with PV price of 3000\$/kW.

for PV prices of 2400 and 1800 \$/kW respectively while battery and diesel fuel prices are varied. These show that the transitions discussed above occur even earlier at lower PV prices, as the system is better able to take advantage of the cheaper storage.

Table (3) shows the technologies sizes of different cases. Total cost of hybrid system increases when the diesel fuel cost increases. The total cost increase in hybrid systems is the result of higher PV capacities and also increase in operation cost due to increase in diesel price. The diesel generator size decreases linearly when the diesel fuel increases. Reduction in battery cost affect total carbon emissions decrease more than total cost of system.

(a) Total Cost (\$/year).
The color gradient shows total cost in \$/year.

(a) Total Cost (\$/year).
The color gradient shows total cost in \$/year.

(b) Total Carbon (kg/year).
The color gradient shows total carbon in kg/year.

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Figure 6: Scenario 3 with PV price of 2400\$/kW.

Figure 7: Scenario 3 with PV price of 1800\$/kW.

Figure 8 shows the effect of removing the hot water tank from the energy system when the battery price is constant at 700 \$/kW. In comparison to Figure 4, there is a dramatic increase in system carbon emissions and costs, particularly at high diesel prices.

Discussion

In the previous section, different scenarios are considered to find the effect of energy converter and storage costs as well as diesel fuel cost on the total cost and carbon emission of a hybrid energy system. The results show that hybrid PV systems are beneficial for off-grid buildings. All hybrid scenarios are cheaper than the base case even at current diesel price (\$1/L). Comparison between the base case and the most expensive scenario (battery \$700/kWh, PV

\$3000/kW) at current diesel price highlights that the total cost of the hybrid energy system reduces by 35%. Moreover, the total carbon emissions is 40% of the first scenario. However, this is largely due to the annualization of investment costs over the lifetime of the technology: at the current diesel price, the base case investment cost C_{Inv} is 11 \$/year and the operational cost C_{op} is 466\$/year. In comparison, the most expensive hybrid system the investment cost is 118\$/year and the operation cost is 194\$/year. Therefore, even though over 25 years the hybrid system is cheaper, it requires ten times the initial investment.

The effect of diesel fuel price on hybrid energy systems is studied. Diesel price is typically high in remote communities due to unique geographical and operational limitations. Many factors affect

Table 3: Capacity table.

	Diesel price (\$/L)	Diesel generator size (kW)	Heat pump size (kW)	PV size (kW)	Battery size (kWh)	Carbon emissions (kg/year)	Cost (\$/year)
Base case	1	0.5	0.1	0	0	1248	477
Base case	3	0.5	0.1	0	0	1248	1409
Base case	5	0.5	0.1	0	0	1248	2341
Battery \$700/kWh,PV \$3000/kW	1	0.5	0.5	1.2	0.5	518	311
Battery \$700/kWh,PV \$3000/kW	3	0.4	0.7	2.9	2.1	196	520
Battery \$700/kWh,PV \$3000/kW	5	0.3	1.3	4	2.7	120	634
Battery \$200/kWh,PV \$1800/kW	1	0.4	0.5	2.4	1.9	249	225
Battery \$200/kWh,PV \$1800/kW	3	0.3	0.6	4.6	3.9	93	347
Battery \$200/kWh,PV \$1800/kW	5	0.2	0.6	6	5.3	45	392

(a) Total Cost (\$/year).

The color gradient shows total cost in \$/year.

(b) Total Carbon (kg/year).

The color gradient shows total carbon in kg/year.

Figure 8: Scenario 4 (without hot water tank).

diesel price in remote communities including mode of transportation (by air, barge or road), remoteness of location and etc. Modelling the energy system based on different diesel fuel prices makes it possible to determine the impact of this on energy systems in the future, allowing more robust decisions to be taken now to account for this.

The effect of hot water storage is further studied for varying PV panel prices, since the changes in hot water demand affect electricity demand. The exclusion of a hot water tank results in much higher carbon emissions since the operation of the diesel generator increases. This highlights the importance of the hot water storage system for buffering changes in PV availability, since hot water storage is always significantly cheaper than batteries.

Therefore, hot water tank installation will improve the total cost of the hybrid energy system as well as carbon emission reduction. This shows the importance of adding a water tank to these systems and should be considered in future studies as an option to lower environmental impact. A limitation of this study is that it did not consider the impact of hot water demand timing, or the input water temperature, storage duration and output water temperature. In future work, the temporal distribution of hot water demand as well as different efficiency factors of the hot water tank and their importance will be studied.

Conclusions

This paper presents the modelling and optimization of a hybrid system for supplying electricity and hot water to an off-grid building in Victoria, Canada. The optimal sizing of the system is found by using the energy hub model and the results are compared for different diesel fuel prices. Furthermore, it is explored how different scenarios of future PV and battery cost affect optimal system choice and performance. Our results show that hybrid systems are 35% cheaper (over a 25 year lifespan) than the base case using a diesel generator. This situation gets worse at higher

diesel prices, and is helped by lower PV and battery prices, but not in a linear manner. This is illustrated using contour plots that show the impact of different combinations of variables. Moreover, the importance of hot water tank for buffering PV fluctuation is shown in the results.

From all the scenarios studied in this work, it is readily observed that hybrid energy systems are applicable solution to both economic and environmental concerns if renewable energy source are taken seriously when designing energy systems. Canada's remote communities are different, and there is no simple solution that will address their unique energy systems needs. In future, we will consider different weather data across Canada. In addition, we will take into account the modelling and optimization of energy systems to supply heating and cooling load in future work.

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