Optimal Sizing of Storage Technologies for On-grid and Off-grid Systems

by

Azin Rahimzadeh
B.Sc., University of Isfahan, 2012
M.Sc., Sharif University of Technology, International Campus, 2015

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We acknowledge with respect the Lekwungen peoples on whose traditional territory the university stands and the Songhees, Esquimalt and W̱SÁNEĆ peoples whose historical relationships with the land continue to this day.

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ABSTRACT

The challenge of managing present and projected electricity energy needs along with targets of mitigating CO_2 emissions leads the energy systems to reduce reliance on fossil fuels and rely on more energy from renewable sources. Integration of more renewable energy technologies to meet present and future electricity demand is facing more challenges in matching the trade-off between economic, resilient, reliable and environmentally friendly solutions. Energy storage technologies provide temporal resilience to energy systems by solving these challenges. Energy storage systems can improve the reliability of energy systems by reducing the mismatch between the supply and demand due to intermittency of renewable energy sources.

This thesis presents a comprehensive analysis of various energy storage systems analyzing their specific characteristics including capital cost, efficiency, lifetime and their applications. Different hybrid energy systems are designed to analyze the impacts of renewable and non-renewable energy sources and energy storage systems in residential on-grid and off-grid buildings and districts. An optimization analysis is performed to determined which technologies and integration of technologies provide the most economic solution to meet electricity energy demands. The analysis in this thesis employ building simulation tool to model residential building and real data sets to explore the different electricity profile effects on the results. The environmental effect of hybrid energy systems comparing with base cases of conventional energy systems or grid connection are also analyzed in this thesis.

Results shows that feasibility of energy storage systems is a factor different variables including capital cost of energy converters and energy storage systems, cost of input streams (grid electricity in on-grid systems and diesel fuel in off-grid systems, energy demand profiles and availability of renewable energy sources. The on-grid single and district buildings do not choose storage technologies with current costs due to cheap grid electricity. Reduction in cost of renewable energy technologies and/or energy storage systems (basically Li-ion battery) results in more energy storage installation. In off-grid systems (residential and districts), Li-ion battery and pumped hydro are the main storage systems which balance the daily and seasonal energy demands.

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Author Contributions

This thesis consists of one peer reviewed conference publication and two journal article manuscripts that will be submitted to peer reviewed journals. The author contributions are clarified below.

Rahimzadeh A., Evins R. **The Effect of Fuel and Storage System Price on the Economic Analysis of Off-grid Renewable Energy Systems.** *Proceedings of Buildings Simulation 2019, IBPSA, 4-6 September, Rome, Italy.*

A.R. developed the methodology, performed the analysis and wrote the manuscript. R.E. supervised the project, contributed to the methodology and revised the manuscript.

Rahimzadeh A., Christiaanse T.V., Evins R.,**Optimal storage systems for residential energy systems in British Columbia.** *Prepared for submission to Applied Energy journal*

A.R. developed the methodology, performed the analysis and wrote the manuscript. T.C. contributes to the methodology and revised the manuscript. R.E. supervised the project, contributed to the methodology and revised the manuscript.

Rahimzadeh A., Christiaanse T.V., Evins R.,**Energy transition complexities in off-grid remote communities** *Prepared for submission to Applied Energy journal*

A.R. developed the methodology, performed the analysis and wrote the manuscript. T.C. contributes to the methodology and revised the manuscript. R.E. supervised the project, contributed to the methodology and revised the manuscript.

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Chapter 1

Introduction

The largest greenhouse gas (GHG) emissions source with level of 25% of total global GHG emissions belongs to electricity and heat production due to burning of fossil fuels [4]. Additionally, global electricity demand has increased over the past years [1]. As a result, use of renewable energy sources (RES) has taken into account in electricity sector in recent years. Despite the advantage of renewable energy sources, the major disadvantages of RES (mainly in case of wind and solar energy) is their intermittency over time. This fluctuation results in a great mismatch between energy generation and energy demand. This mismatch would be higher when the share of renewable energy increases. To deal with the temporal mismatch, storage systems are one the main solution to solve this issue [2].

Electricity generation from fossil fuels, mainly coal and then natural gas, produce 10% of total emissions in Canada at 2017 [3]. In 2017, 7% of electricity in Canada came from renewables which has 18% increase comparing with 2010 [6]. According to Natural Resource Canada, waste less energy and clean power are two pathways out of fours for Canada energy transition [5].

As a result, it is required to study possible low carbon energy systems in residential electricity sector. In this thesis, various possible electricity energy systems for different residential buildings scale are studies. Moreover, various energy storage systems are analyzed to find the feasible storage technologies in residential sectors. Moreover, different factors including renewable energy converters properties (mainly solar and wind), energy streams (diesel fuel and grid connection), different shares of renewables and various properties of storage systems are studied.

There are many studies that examines the benefits of energy storage system and methods in optimal design of energy system. Each chapter has studied the literature reviews on these studies, therefore to decrease the repetition a separate literature review chapter is not included in this thesis.

The section of this thesis are summarized as following:

- Chapter 2 is a conference paper that was presented at ”Building Simulation 2019” conference in Rome, Italy (4-6 September). In this paper, an optimal design of an off-grid energy system for single building is studied. For scenarios are considered to to find the importance of energy storage systems in energy system, the effect of energy streams cost and energy converters impact on total cost and carbon emissions.

- Chapter 3 is journal paper that is ready for submission to the Journal of Applied Energy. The paper study different energy storage systems and comparing their properties to filter them by applicability and cost effectiveness. Moreover, an optimization model is used to design optimal energy systems for different residential building scales. As result, the feasible energy storage systems for different scales in on-grid and off-grid system achieved.

- Chapter 4 is another journal paper ready for submission to Applied Energy journal. It focuses on modeling the energy systems of remote communities in Canada. Different factors of energy systems are studied in this paper which results in a wide range of choices based on the existing limitations and priorities in remote communities.

- Last chapter is combining the the findings of all chapters.

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Chapter 2

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

Proceedings of Building Simulation 2019, IBPSA, 4-6 September, Rome, Italy

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2.1 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.

2.2 Introduction

There are over 280 remote communities in Canada which use diesel generators to meet electricity demand [17, 4]. 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 [17]. Moreover, fuel prices are highly dependent on type of transportation to site [17]. 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 [18]. The simulation in this study results indicate that the hybrid system provides higher system performance and reliability than photovoltaic or wind alone. In 2012, [3] 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 [16]. A multi-objective optimization problem to minimize cost and life cycle emissions of an off-grid PV-wind-diesel-battery storage has been done ([6]). 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 [8]. [19] presents a review of software tools for hybrid renewable energy systems. In [12], an optimization for system operation based on energy demand supply, system cost and emissions is done with the HOMER software program. Furthermore, [14, 2, 1] 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 [13]. 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 [15] for the UK. The results show integrating PV panels with a hot water tank is the most advantageous economic solution. In [5], 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 [14] 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 [18] 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.

2.3 Method

2.3.1 Energy hub model

The energy hub model was developed to manage energy flows in a single building, building complex, city or country [11]. 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 [9] 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 2.1, 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 [9].

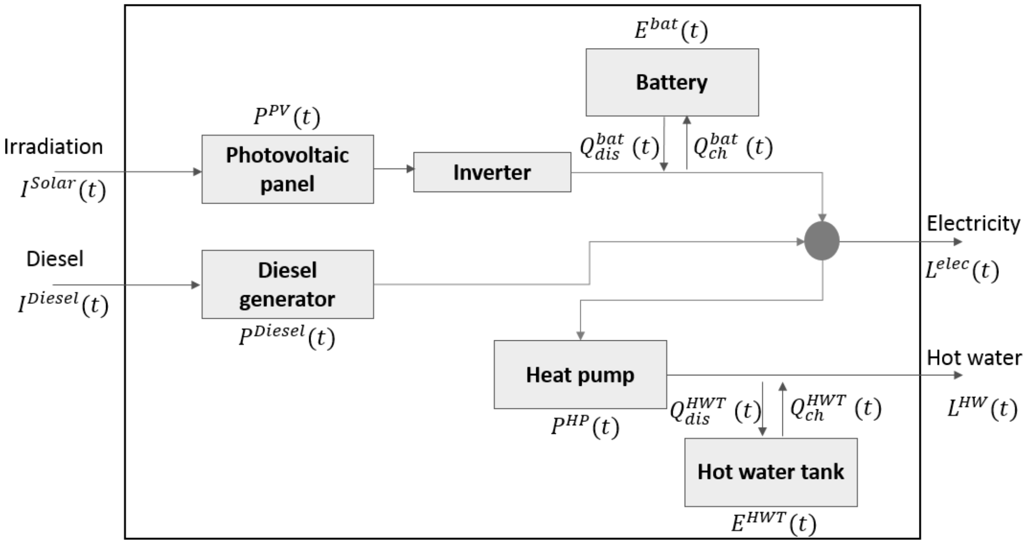

Figure 2.1: Energy hub model.

2.3.2 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 (2.1). 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 (2.1) can be rearranged to equation (2.2) to allocate all decision variables P in the energy hub model and to include storage into the demand and supply balance. In equation (2.2), θ represent energy conversion matrix in spare form (see Table 2.1) which has one column per decision variable P.

$$L(t) = C \times I(t) \tag{2.1}$$

$$L(t) = \theta \times P(t) + e_{ch}Q_{ch}(t) - e_{dis}Q_{dis}(t) \tag{2.2}$$

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

2.3.3 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 2.1. In addition, there are limits on each conversion according to the capacity of technologies (2.3).

$$P^i(t) \leq P^i \leq P_{max} \tag{2.3}$$

Where P_{max} is the maximum capacity of each converters (Table 2.1). The capacity P is a decision variable of the optimization, allowing the energy technologies to be sized and P(t) is the hourly flow.

Table 2.1: 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.

2.3.4 Objective function

For optimizing the proposed energy system a linear function is considered, aiming for minimal equivalent annual cost (EAC), Equation (2.4). EAC is the annual cost of installing and operating a system over its lifetime. EAC is calculated by dividing the net present value (NPV) by an annuity factor A(t,r).

$$\min EAC = \frac{C_{Inv}}{A(t,r)} + C_{op} \tag{2.4}$$

Table 2.2: 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	-

With:

$$C_{Inv} = \sum_{i,j}(C_{Inv}^{i}P^{i} + C_{Inv}^{j}E^{j}) \tag{2.5}$$

$$C_{op} = \sum_{i} I^{i}(t)C_{f}^{i} \tag{2.6}$$

$$A(t,r) = \frac{1 - \frac{1}{(1+r)^{t}}}{r} \tag{2.7}$$

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 2.1). P and E are capacity of each technology which will be determined by the optimization model.

2.3.5 Storage

Storage systems are necessary to match supply with demand. The storage level at each time step is shown in (3.7).

$$E(t+1) = (1 - n_s)E(t) + Q_{ch}(t) - Q_{dis}(t) \tag{2.8}$$

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 storage [1].

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[1] In 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

The charge and discharge at each time step should be lower than the maximum charge and discharge according to technology properties (3.9, 3.10).

$$0 \leq Q_{ch}(t) \leq Q_{ch}^{max} \tag{2.9}$$

$$0 \leq Q_{dis}(t) \leq Q_{dis}^{max} \tag{2.10}$$

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.

$$E_{min} \leq E(t) \leq E_{max} \tag{2.11}$$

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.

$$E(0) = E(8760) \tag{2.12}$$

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

2.3.6 Energy scenarios

Four different scenarios are listed in Table(2.2). 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 2.1 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 [21] and PV panels costs are lower than the current price, at 3000 \$/kW, to 1000 \$/kw. According to [10], 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

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could be avoided by shading the PV array at times of oversupply.

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 Python[2].

2.3.7 Load and Irradiation data

Electrical demands are calculated using an EnergyPlus model with the EPW weather data for Victoria, a nearby weather station [7]. 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 demand is required for lighting, appliances and electronics (laptop and mobile phone). The total area of the house is 200 m^2. 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 [20]. Figure 2.2 illustrates the hourly PV energy available, which was calculated using irradiance values for the roof in the EnergyPlus model.

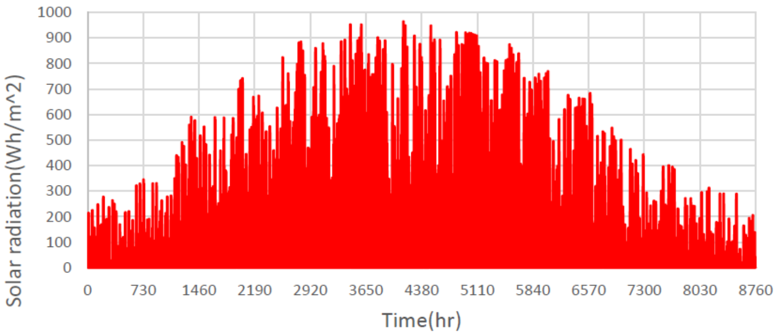

Figure 2.2: Hourly profile for solar radiation in Victoria, Canada (Wh/m^2).

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[2] https://gitlab.com/energyincities/python-ehub

2.4 Results

Figure 2.3 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).

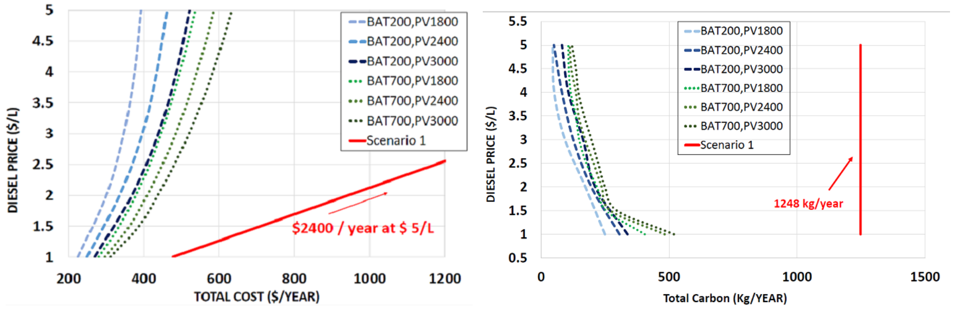

Figure 2.3: Optimal cost and total carbon emissions for various cases.(Left figure:A comparison of the optimal cost values for different cases. The base case (diesel only) is shown in red, but truncated because the cost is so high at \$5/L.; Right figure: A comparison of the total carbon emissions values for different cases. The base case total carbon emissions are 1248 kg/year for all fuel costs.)

In the second scenario, the storage system price is constant (700 \$/kWh) but PV panel cost and diesel fuel price are varied (PV between \$1000 and \$3000 and diesel fuel from \$1/L to \$5/L). Figure 2.4 illustrates how the total cost and total carbon emissions change 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 2.5 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

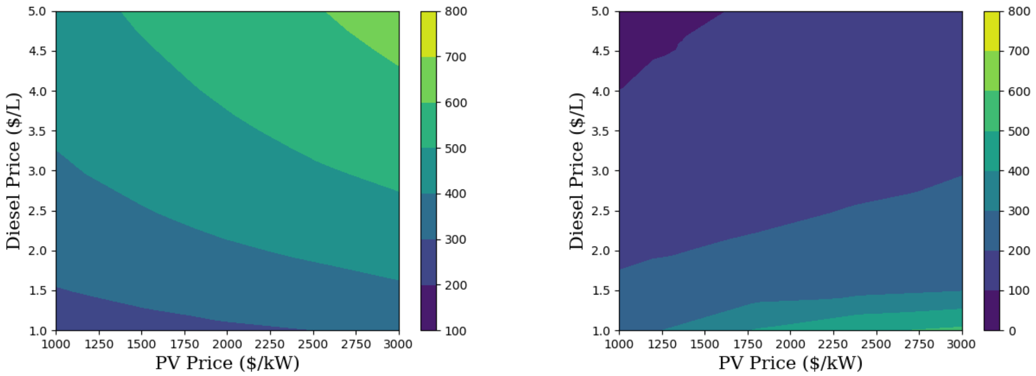

Figure 2.4: Scenario 2 (Energy storage system cost is constant).(Left figure: Total Cost ($/year). The color gradient shows total cost in $/year.; Right figure: Total Carbon (kg/year). The color gradient shows total carbon in kg/year.)

diesel prices these transitions occur earlier and more dramatically.

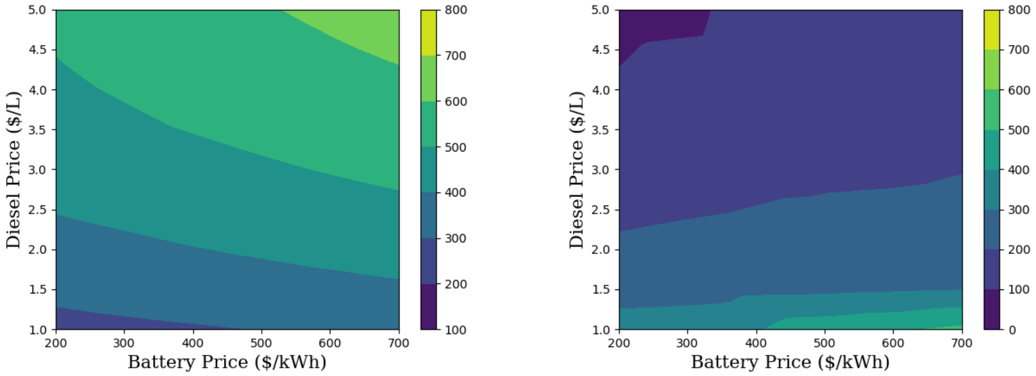

Figure 2.5: Scenario 3 with PV price of 3000$/kW. (Left figure: Total Cost ($/year).The color gradient shows total cost in $/year.; Right figure: Total Carbon (kg/year).The color gradient shows total carbon in kg/year.)

Figure 2.6 and 2.7 show total cost and carbon emissions 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 (2.3) 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

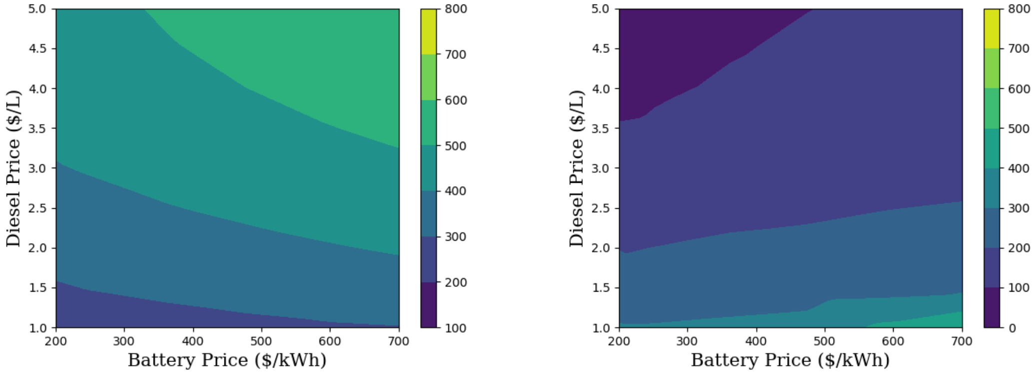

Figure 2.6: Scenario 3 with PV price of 2400$/kW. (Left figure: Total Cost ($/year).The color gradient shows total cost in $/year.; Right figure: Total Carbon (kg/year).The color gradient shows total carbon in kg/year.)

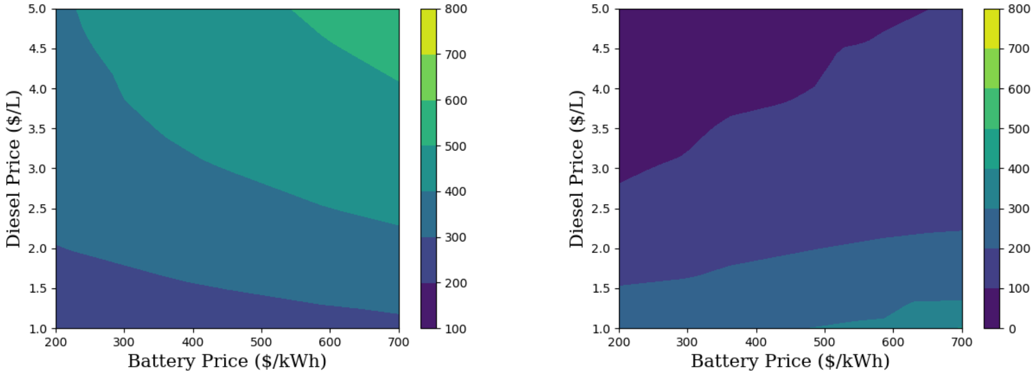

Figure 2.7: Scenario 3 with PV price of 1800$/kW. (Left figure: Total Cost ($/year).The color gradient shows total cost in $/year.; Right figure: Total Carbon (kg/year).The color gradient shows total carbon in kg/year.)

fuel increases. Reduction in battery cost affect total carbon emissions decrease more than total cost of system.

Figure 2.8 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 2.4, there is a dramatic increase in system carbon emissions and costs, particularly at high diesel prices.

Table 2.3: 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

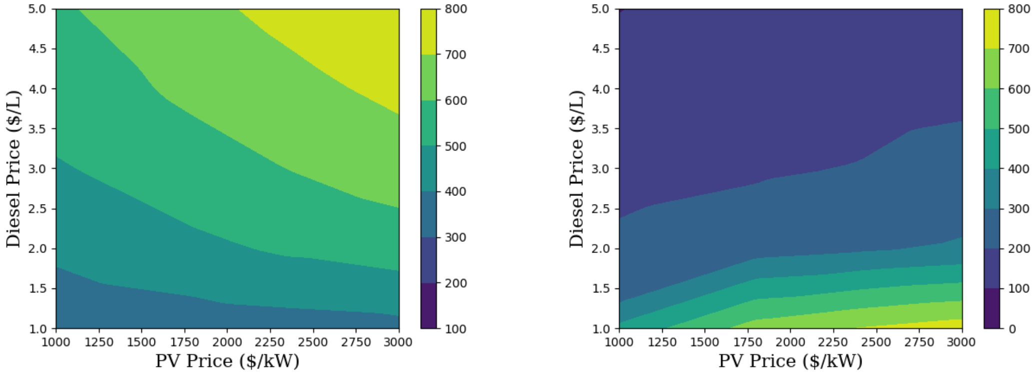

Figure 2.8: Scenario 4 (without hot water tank). (Left figure: Total Cost ($/year).The color gradient shows total cost in $/year.; Right figure: Total Carbon (kg/year).The color gradient shows total carbon in kg/year.)

2.5 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 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.

2.6 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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Chapter 3

Optimal storage systems for residential energy systems in British Columbia

Prepared for submission to Applied Energy journal

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3.1 Abstract

In recent years, deployment of low carbon energy systems to supply electricity in residential buildings has increased. These energy systems typically integrate different renewable energy resources with energy storage systems to meet electrical energy demand. This paper applies the "energy hub" model to various energy systems for residential buildings in British Columbia considering several scenarios. We explore the energy system changes in on-grid, off-grid and 100% renewable scenarios. In on-grid systems, the trade off between grid connection and energy storage is explored; the results shows that even the cheapest energy storage system is not feasible with the current cost of grid electricity. For off-grid systems with a diesel generator, storage technologies are used in some energy systems, however the systems still have carbon emissions. Finally, for 100% renewable off-grid systems, both Li-ion and pumped hydro storage systems are used to handle diurnal and seasonal intermittency.

3.2 Introduction

Global electricity demand has grown rapidly over the last decade [1], often met using fossil fuel power plants. To achieve targets of mitigating CO_2 emissions, electricity generation should move forward with decreasing reliance on fossil fuels and growing use of renewable energy sources.

The major disadvantage of renewable energy sources is that they are, in the case of wind and photovoltaic (PV) systems, non-dispatchable due to their stochastic fluctuation over time. The intermittency and variability of renewable energy sources rise a great challenge to balance the demand and supply. Currently in British Columbia (BC),Canada, this mismatch is managed by exporting excess renewable energy production to the grid and then importing the electricity from grid when renewable energy production can not meet demand. The temporal mismatch will be more serious when the fraction of renewable energy resources increases.This mismatch means that storage technologies are a key solution [11][18]. Recent research has reviewed energy storage system technologies [10]. which can capture produced energy at one time and use it at a future time. The energy storage technologies have different characteristics and application, and there is not any single storage technology which stands out all in the characteristics. These characteristics include storage capacity, depth of charge, discharge time, efficiency, durability, autonomy and cost. Integrating energy storage into energy systems will cause different environmental and economic impacts due to different energy storage system characteristics, power systems application and demand profiles [3][21]. In order to compare these characteristics with the multiple applications of energy storage systems, further analysis is needed to assess the feasibility of energy storage technologies in different energy systems. A variety of techniques are used to supply the electricity demand in the most cost effective way [20].

In this paper the integration of different renewable and non renewable energy systems with energy storage for different residential district scales will be analysed. It is challenging to find the best combination and sizes of the most cost effective technologies which supply electricity demand, which depends on the hourly energy demand and renewable availability, availability of energy systems technologies and system characteristics and costs. This problem can be solved using the ”energy hub” model formulation, which optimizes an energy system operation and sizing [15][17]. The energy hub model is well suited to analyse energy flows at different scales [17]. A residential energy hub model is studied in [6] to supply electrical, heating and cooling demand using various energy inputs. In this paper,we perform a comprehensive analysis of different energy storage technologies considering their specific characteristics.We compare different properties including capital cost, lifetime and efficiency of storage system, with a focus on their application in residential buildings. The novel contributions of this study are:

- First, we conduct a review of energy storage technologies and filter them by applicability and cost effectiveness.
- We study system changes by varying different properties of systems including the capital cost of renewable energy systems and energy storage systems.
- All analysis are performed using an optimization method in different district sizes, different regions for different scenarios of on-grid and off-grid.
- A sampling method is used to get the demand profile for single and district scales from 2000 data set.
- ϵ-constraint method is used for finding transition cost of storage technologies.
- The results are presenting energy demand (MWh) versus energy capacities (kWh).

3.3 Energy Storage Technologies

The global electricity storage capacity in 2017 was 4.67 TWh, 96% of which is pumped hydro storage [28]. It is expected that total energy storage capacity will increase 3 fold by 2030, largely driven by growing renewable energy generation [28]. There are different methods to classify energy storage technologies. One common approach is based on the form of stored energy which can be classified into 5 groups: electrochemical, mechanical, chemical, electrical and thermal energy storage systems [9]. In this research, thermal energy storage technologies are not considered. In Figure 3.1, the energy storage systems considered in this work are shown.

A brief description of each type of energy storage system is given in the following sections.

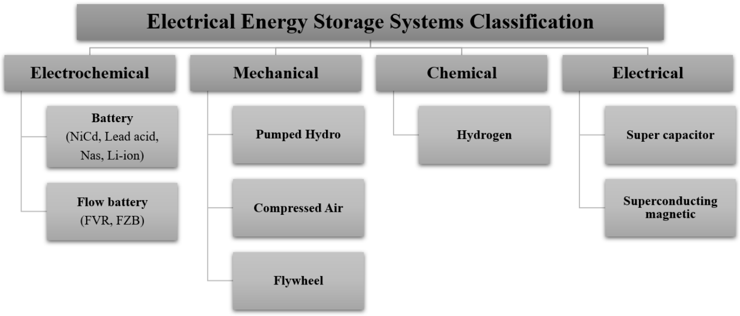

Figure 3.1: Classification of Electrical Energy Storage Technologies according to Energy Form (This figure includes energy storage systems considered in this work.)

3.3.1 Electrochemical

The operating principle of electrochemical storage systems, commonly referred to batteries, is electricity conversion to chemical energy during charging periods and then converting back from chemical energy to electricity for discharging. many types of batteries can be used in energy systems: Nickel-Cadmium (NiCd), Sodium-sulfur (Nas), Lithium ion (Li-ion), Lead-acid, Zinc Bromine (ZnBr), and Vanadium redox (VR) [22].

3.3.2 Mechanical Storage

In mechanical storage, electrical energy is converted into potential energy for storage. Pumped hydro energy storage (PH), flywheel and compressed air energy systems (CA) are considered in this work.

The pumped hydro storage is a hydroelectric storage which stores electrical energy as gravitational potential energy. Water is pumped to a higher level reservoir during low electricity demand and then powers turbines to generate electricity during the high electricity demand. The height between high and low reservoir and water volume determines the amount of stored energy during the process. PHES is the most mature storage system with respect to installed capacity, with 169 gigawatts out of 176 gigawatts installed globally in 2017 [28]. The feasibility of PHES at small scales, relevant to buildings, is analyzed in [12] where all components of PHES are modeled in different scenarios. This also includes analysis of an integrated pumped hydro system in a building in France which they find PHES in buildings to be technically feasible. The limitations in this system ,for example lack of economic data in small scale systems and large volume water reservoir, lead PHES as an inappropriate energy storage in buildings.

The idea of compressed air energy storage (CA) is to use exess electrical energy to compress air and then release the compressed air to generate electricity via a turbine. The typical capacity of CA range from 50 to 300 MW with an efficiency of 70% with pressure of 70 bars [24]. The main drawback to implement CA in energy systems is the high investment cost of the plant due to identifying an appropriate geographical location, as air is usually stored in underground chambers. Flywheel energy storage stores electric energy by converting it to kinetic energy by increasing and decreasing the rotational speed of a large weight. Flywheels have potential in energy systems that require high power balancing in a short time period [4].

3.3.3 Chemical

Chemical energy storage technologies convert into a chemical fuel for storage. The most common form is hydrogen energy storage systems (H), which requires two processes to store energy and to generate electricity: a fuel cell and an electrolyzer.Despite the low cost of hydrogen storage systems, the costs of electrolyzer and fuel cell are high, limiting their applicability at small scale.

3.3.4 Electrical

Electrical storage is mainly realized by super capacitor (SC) and superconducting magnetic (SM) energy storage. The main features of electrical storage systems are high power density, fast time response (milliseconds) and fast discharge period (under 1 minute). The main disadvantages of these systems are high self-discharge and high capital cost. Due to the quick time response and high losses, these storage systems are not considered in this research.

3.3.5 Technical and Economic Comparison of Energy Storage Systems

The previous section has shown that a wide range different technologies exist to store electrical energy. Different properties include storage efficiency, power and energy related cost, response time, lifetime and environmental impact. To find optimal applications of storage systems in energy systems, economic and technical aspects must be analysed together. Table 3.1 shows different characteristics of the storage technologies. There are some challenges in finding cost and performance of storage systems since published values are not always defined clearly. Limited actual values of storage systems characteristics is another challenge due to rapid changes in the market. Literature published after 2016 are used here. All prices presented in this research are converted to CAD$.

The time response of the storage system is not considered as a decision variable in this work, which uses a one hour time step throughout. Electrical energy storage systems (SC and SM) are not considered as they are only suitable for fast response times.

Table 3.1: Energy storage system characteristics.

Energy Storage Technology	Efficiency (%)	Energy Capital Cost ($CAD/kWh)	Power Capital Cost ($CAD/kW)	Lifetime (years)
Nickel-Cadmium(NiCd)[10]	60-65	520-3120	650-1950	10-20
Lead-acid[2]	70-90	260-520	390-780	3-15
Sodium-sulfur(NaS)[10]	80-90	390-650	1300-3900	10-15
Lithium ion(Li-ion)[16][5]	85-90	272-4940	91-5200	5-15
Vanadium redox(VR)[10]	70-85	195-1300	780-1950	5-10
Zinc Bromine(ZnBr)[10]	75	195-1300	910-3250	5-10
Hydrogen(H)[2][10]	65-75	20-130	650-13000	5-20
Flywheel(F)[2]	93-95	1300-18200	325-455	>15
Pumped Hydro(PH)[2]	75-85	6.5-130	2600-5590	40-60
Compressed Air(CA)[10]	70-89	3-156	520-1300	20-40
Super Capacitor(SC)[2]	90-95	650-1300	260-520	>20
superconducting magnetic(SM)[2]	95-98	1300-93600	260-636	>20

Energy storage systems typically consist of storage units and power conversion systems. In table 3.1, storage unit and power conversion system cost are presented as energy capital cost (CAD/kWh) and power capital cost (CAD/kW) respectively. To determine the total cost of a storage system, both energy and power capital costs should be considered:

$$\begin{gathered}\text{Total Energy Storage Cost (CAD/kWh)} = \\ \text{Energy Capital Cost (CAD/kWh)} + \text{ Power Capital Cost (CAD/kW)/Duration(h)}\end{gathered} \tag{3.1}$$

As shown in Table 3.1, there are three variables determining the feasibility of storage systems in an energy system: cost, efficiency and system lifetime. To simplify these variables, we calculate the equivalent annual cost (EAC) and efficiency of all storage systems, as shown in Figure 3.2. EAC is the annual cost of accounting for the time value of money via the interest rate. Each system over its lifetime, EAC allows to compare cost effectiveness of storage systems that do not have equal lifetimes. Equation 3.2 gives the formula of EAC.

$$EAC = \frac{Capital\ cost\ (CAD/kWh) * Interest\ rate}{1 - \frac{1}{(1+Interest\ rate)^n}} \tag{3.2}$$

Where n is the lifetime of the system. Figure 3.2 shows the equivalent annual cost of energy (CAD/kWh) in the left plot and total capital cost (based on equation 3.1) in the right plot. In this figure, minimum and maximum EAC of all storage technologies are shown based on the information in Table 3.1. For example with capital cost of 130 \$CAD/kWh, interest rate 8% and lifetime of 20, the EAC would be 10.9 \$CAD which is the maximum EAC of pumped hydro in Figure 3.2(a). To calculate the EAC, we consider the minimum lifetime of each technology (except Li-ion which 11 years is considered). The efficiencies in Figure 3.2 are the mid values from Table 3.1.

The EAC of storage systems is significantly lower for most of the technologies in comparison to total EAC (sum of storage and converter). For example, for Pumped hydro the EAC of the storage is smaller than for Li-ion battery storage, which may lead to the choice of this technology. However, when it comes to the EAC of the total storage system including storage units and converters (b) Li-ion batteries are the cheaper option.

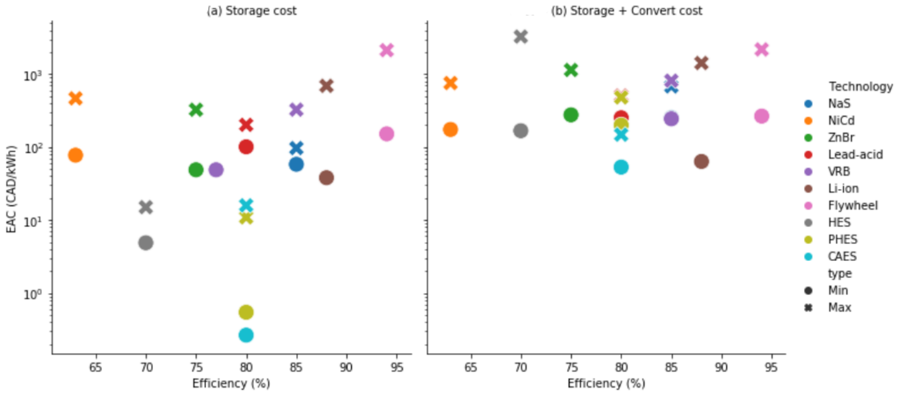

Figure 3.2: Equivalent annual cost vs efficiency of energy storage systems (a): Storage cost, (b): Storage and converter Costs

Comparing all storage technologies suitable for residential districts, Li-ion and CA have the lowest cost. Despite the low EAC and high efficiency of CA, this system need a large amount of space and specific geological features like underground spaces [8]. For this study, we have therefore selected Li-ion and PH as good candidates for residential sector energy storage in BC.

3.4 Methods

Energy Hub Model

In this research, an energy hub model is used to explore the optimal designs of energy systems. The energy hub model has been developed to represent the interaction of various energy conversion and storage system [17]. It introduces a framework to analyze and optimize the interaction of energy flows of different energy conversion and energy storage systems. In [15], a new formulation of energy hub is presented to address operational constraints which are representative of system performance. Many different energy systems can be modelled and optimized using the energy hub model, including multiple inputs energy carriers which are converted to multiple outputs. A conversion matrix consisting of conversion efficiencies is used to connect inputs and outputs. In addition to energy conversion systems, the model can include energy storage technologies which store energy and using it later. The key equations and constraints of the energy hub model are outlined below, following [15].

3.4.1 Energy Hub equation

The most important equation of the energy hub model is the energy balance of the system (Equation 3.3). According to this equation, the electrical energy demand of the system at each time step must be equal to the sum of the output energy from each converter (converter efficiency θ times input energy P), the energy from storage (discharge efficiency e_{dis} times discharge energy Q_{dis}), the imported energy from the grid (E_{imp}) minus the energy used to charge the storage (charge efficiency e_{ch} times charge energy Q_{ch}), and the energy exported to grid. In off-grid systems, imported and exported energy are not considered, so these terms are set to zero.

$$L(t) = \theta_{i,j} \times P_j(t) - e_{ch}Q_{ch}(t) + e_{dis}Q_{dis}(t) + E_{imp}(t) - E_{exp}(t) \qquad (3.3)$$

In this equation, $\theta_{i,j}$ represents the efficiency of converter j that converts input energy flow of i to output j.

Equation 3.4 defines the objective function of the optimization problem, which in this work is to minimize cost. In this equation, the equivalent annual cost (EAC) of the capital costs of all converters and storage systems summed with the operation cost. EAC is capital cost of ($C^j_{Converter}$ and $C^k_{storage}$) times capacities of converters (P^j) and storage systems (E^k) divided by the annuity factor $A(t,r)$. where t is lifetime of the each technology in years and r is the annual interest rate as a percentage. Fixed capital costs and maintenance costs are not included in this equation.

$$\min Cost = \sum_j \frac{(C^j_{Converter}P^j)}{A_j(t,r)} + \sum_k \frac{(C^k_{storage}E^k)}{A_k(t,r)} + \sum_j P_j(t)C^j_{op} \tag{3.4}$$

$$A(t,r) = \frac{1 - \frac{1}{(1+r)^t}}{r} \tag{3.5}$$

The availability of each energy input has some limit, particularly when there are renewable energy technologies in system. For example, the irradiation to PV panels or wind energy from a wind turbine are limited at each time step. This limit is defined in equation 3.6.

$$P_j(t) \leq P^j I_j(t) \tag{3.6}$$

To maintain the storage continuity, equation 3.7 is defined which determines the state of the storage at each time step to be equal to its state in last time step minus storage losses plus charge minus discharge. n_s is storage loss (%) in equation 3.7. In addition, the storage level at the last time step for a year (8760) should be equal to first storage level (0) (equation 3.8). This loop avoids importing a specific value at step 0.

$$E_k(t+1) = (1-n_s)E_k(t) + Q_{k,ch}(t) - Q_{k,dis}(t) \tag{3.7}$$

$$E_k(8760) = E_k(0) \tag{3.8}$$

The charge and discharge at each time step should be lower than the maximum charge and discharge according to technology sites (3.9, 3.10).

$$0 \leq Q_{k,ch}(t) \leq Q_{k,ch}^{max} \tag{3.9}$$

$$0 \leq Q_{k,dis}(t) \leq Q_{k,dis}^{max} \tag{3.10}$$

All converters and storage systems must operate below their capacities as shown in equation 3.11 and 3.12.

$$0 \leq P_j(t) \leq P^j \tag{3.11}$$

$$0 \leq E_k(t) \leq E^k \tag{3.12}$$

Finally, all the technologies capacities themselves are variables to be determined by the model, and are limited by the maximum technology capacity.

$$0 \leq P^j \leq P_{max}^j \tag{3.13}$$

$$0 \leq E^j \leq E_{max}^j \tag{3.14}$$

The energy hub model in this paper is formulated in the PyEhub library [1]. This python library constructs the Mixed Integer Linear Programming (MILP) optimization model, which is then solved using IBM CPlex.

3.4.2 ϵ-constraint method

In previous section, it is explained that the objective function of the optimization model is to minimize the equivalent annual cost of energy system. In some cases, the model may not choose energy storage systems because of their high capital costs. In this cases, we decrease the cost of storage technology to find the feasible cost it in that specific energy system. ϵ-constraint method is applied to find the transition cost of energy storage system. This method in this research is constructed as Figure 3.3. In the first step, a very low storage cost (usually zero) is assumed and the optimization model run (If the storage would not be feasible in this step, there are other variables in model which prevent the storage to install. Then the third cost between initial and

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[1] https://gitlab.com/energyincities/python-ehub/.

secondary cost is considered and rerun the model. If the storage capacity would be higher than zero, fourth point will be chosen between 1 and 3. If the storage capacity would be zero again, fourth point should be between 2 and 3. The higher number of iteration in this process results in closer value to feasible cost.

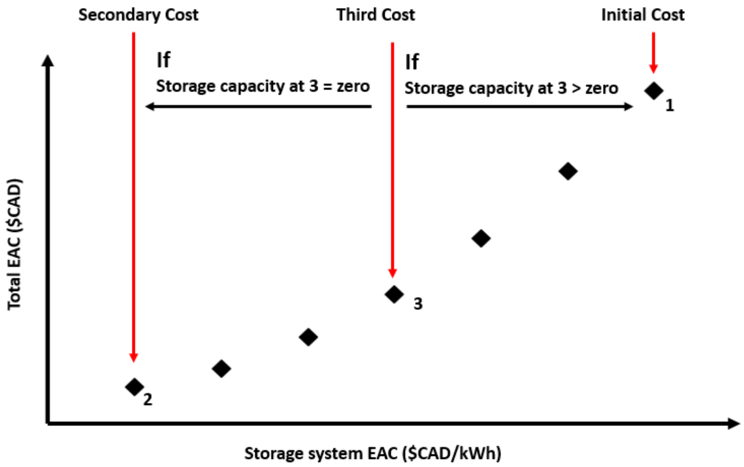

Figure 3.3: ϵ-constraint method

3.5 Scenarios

This paper uses 2000 hourly time series of electricity load data to analyze the feasibility of electrical energy storage systems in residential district in British Columbia (BC). The general flow diagram implemented in this research is shown in Figure 3.4. This diagram has three main parts including input data, modeling and results. The input parts and energy model are discussed in this section. The result part will be discussed in next section.

These data include electricity demand for five different types of residential building: high rise apartment, low rise apartment, row house, single/duplex house and mobile house. All the data contain hourly electricity demands for a whole year. The electricity demand in this data set is for buildings which do not have electrical heating. The data cover four regions in BC including Lower Mainland (LM), Northern (N), Southern Interior (SI) and Vancouver Island (VI) as shown in Figure 3.5.

In this data set, the exact location of buildings are not indicated. Moreover, British Columbia weather can vary significantly influenced by latitude, the Pacific Ocean and the mountains [26]. Therefore, a single location for each region is considered

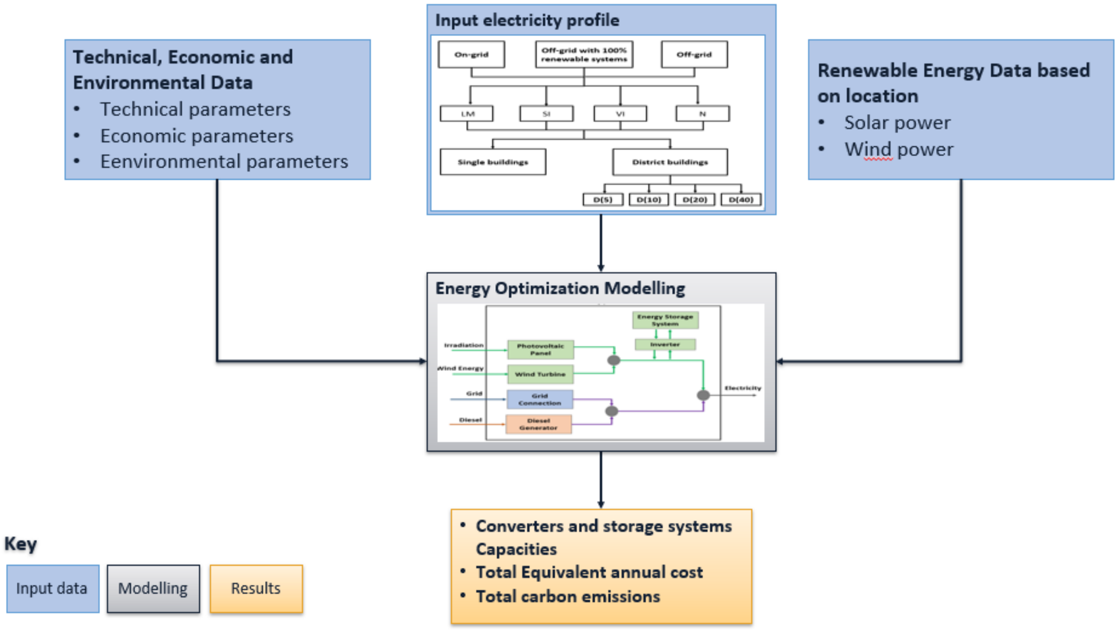

Figure 3.4: Main flow diagram

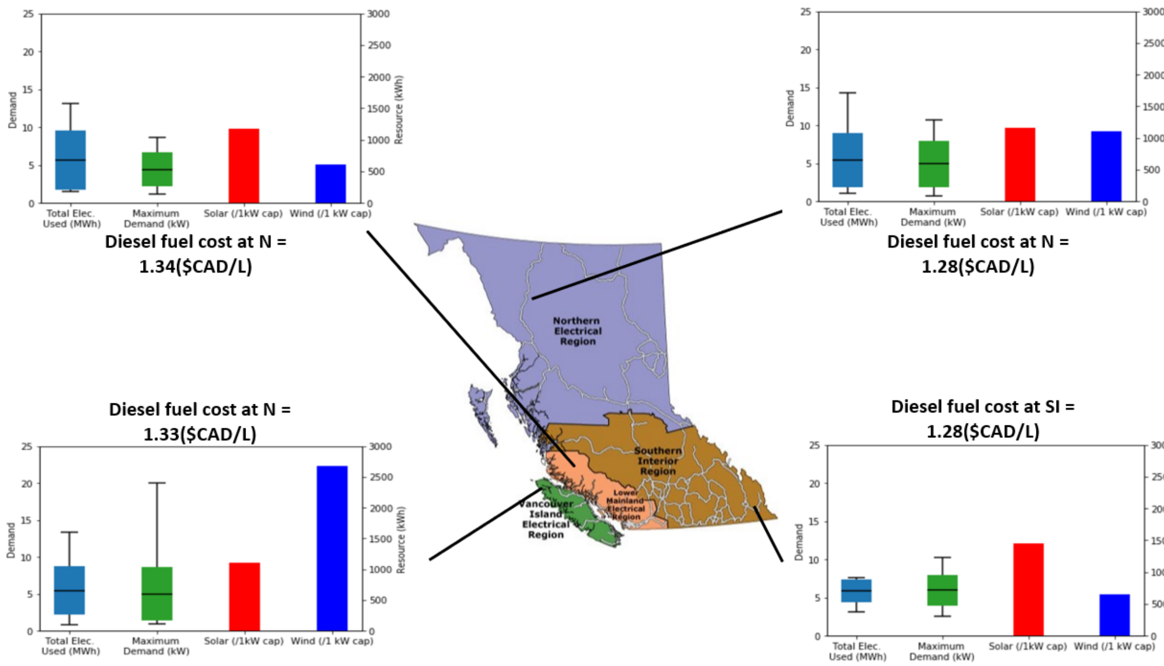

Figure 3.5: British Columbia Electrical Regions (The approximate location are shown for each region)(All plots include the distribution of annual electricity (MWh), distribution of peak demand (kW), annual solar energy (kWh) and annual wind energy (kWh)

for consistency in the model, chosen based on current wind and solar PV farms in BC as shown in Figure 3.5[13]. To find wind and solar energy for each location, an open source platform ”Renewables.ninja” is used[25]. The solar irradiance data is converted into power output in this platform, considering a PV capacity of 1 kW, system efficiency of 17%, tilt angle of 35°and azimuth angle of 180°. In addition, wind speeds are converted into wind power considering a 1 kW capacity turbine, 80 m hub height and turbine model ”Vestas V90 2000”. Finally, diesel fuel cost data are extracted individually for each region [7].

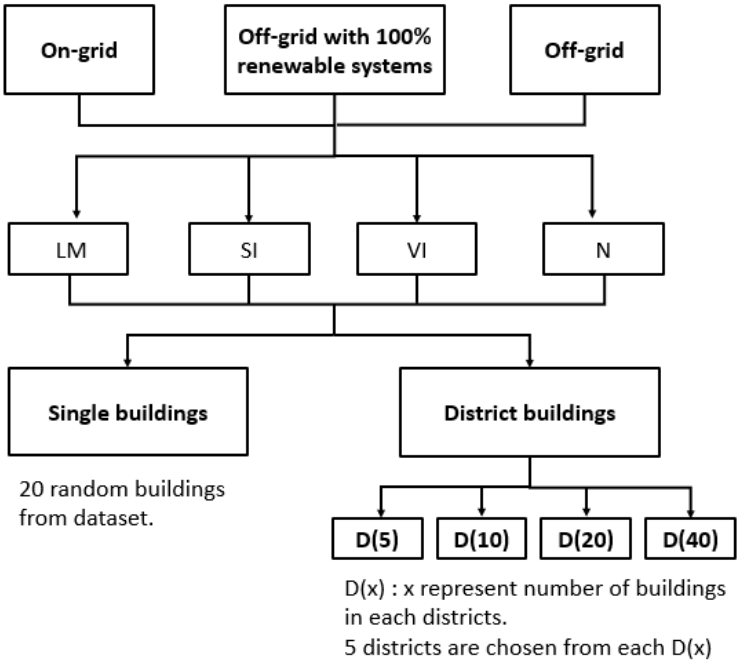

Figure 3.6

Secondly, the data sampling from this data set, demand scale and energy system scenarios are presented in Figure 3.6. In top row of this diagram, three energy scenarios are shown: On-grid, Off-grid and Off-grid with 100% renewables. After selecting the scenario, a region (LM, SI, VI and N) should be chosen. Finally, a electricity demand scale should be chosen, single building or district building. In single buildings scale, 20 buildings are chosen from the data set. In district buildings scale, there are four sizes (x) of districts including D5, D10, D20 and D40. For each district size, x buildings are chosen fro the data set and then sum of them would be the one district of size x. For each district size, this process is repeated 5 times. Therefore, 5 districts from each size results in 20 district buildings with different sized. Therefore, number of electricity inputs to optimization model (in Figure 3.4) is 480.

Renewable energy sources including solar and wind energy are available in all of the energy systems (On-grid, off-grid and off-grid with 100% renewable systems). The on-grid system is connected to the grid electricity to import electricity when it is required, according to charged utility tariffs. Surplus renewable energy can be exported to grid for free or it can be stored in an energy storage system [2].

The off-grid systems are disconnected from the grid, and the electricity demand is provided by solar and wind energy. The off-grid system has a diesel generator but the Off-grid with 100% renewables system does not have the diesel generator option. A schematic of the energy systems that are using in this work is presented in 3.7. According to this figure, the green technologies (PV panel, wind turbine, energy storage system) are the fixed in all energy system which are the main converters and storage systems in off-grid with 100% renewable systems. The grid connection (blue block) is added to the green ones in on-grid systems. Similarly, diesel generator (orange block) is the additional converter to fixed ones in off-grid systems.

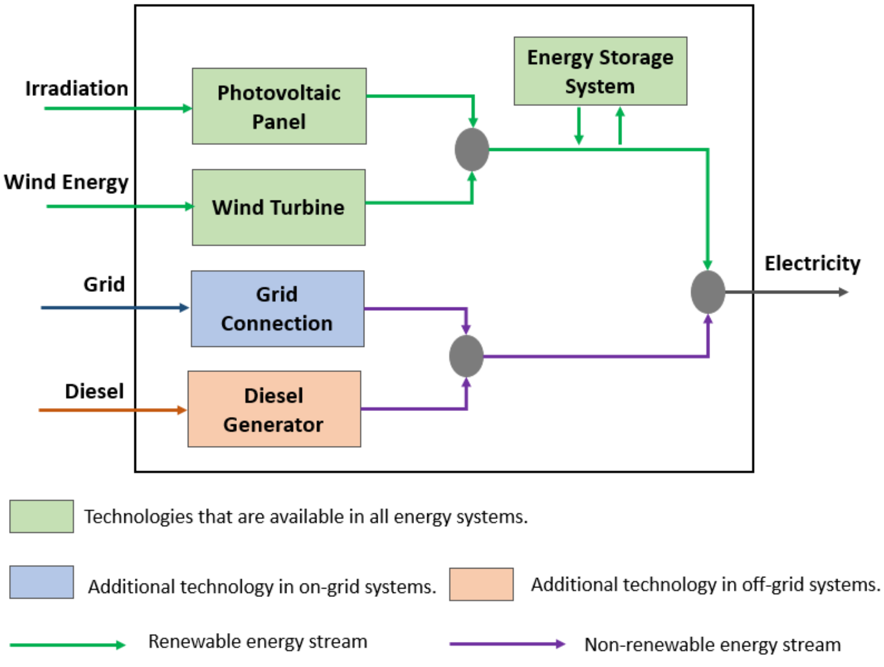

Figure 3.7: Energy hub model in this work

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[2] In our study we reduce the cost of storage to zero to explore the option of any net-metering programs for grid connected buildings and districts. In BC, BC Hydro the province wide utility provides such a program for systems up to 100kW.

Table 3.2: Converter technologies properties in energy hub [27]

Converter	Capital Cost CAD/kW	Lifetime years	Efficiency %
Grid connection	0.001	100	100
PV panels	1606	20	100
Wind turbine	2095	25	100
Diesel Generator	325	30	46

The technical characteristics of converters in energy hub model are indicated in table 3.2. This table shows the capital cost per kW capacity of each converter ($C^j_{converter}$ in equation 3.4), the lifetime used to calculate annuity factor and the efficiency of each converter (θ in equation 3.3) [27][14][19]. The capital costs of renewable energy systems are provided in different references which are calculating based on various analysis. To maintain the consistency in this research, both capital cost of PV panel and wind turbine are derived from the same reference [27]. Grid capital cost is considered a very small value to avoid the model choose the maximum capacity. PV panel and wind turbine efficiency are considered 100% since the efficiency of them are considered previously in converting energy data to power output. Furthermore, it is assumed that the maximum capacity for the converters is 999,999,999 kW. This maximum number is never chosen by the model and is only used to prevent unlimited variables.

In all cases the grid cost assumes to be at 0.14 CAD/kWh [19]. Diesel fuel prices for each region is indicated in Figure 3.5.

Below are the main cases to be explored for scenarios explained earlier.

Case 1 (No storage): In this case, it is assumed that there is not any storage system in energy system. This case is not valid for off-grid 100% RES.

Case 2 (Storage systems): all possible storage systems are included in energy system individually according to tables 1, 2 and 3 properties.

Case 3 (Low cost storage systems): According to Case 2 results, cost of the storage system will be reduced if the storage system is not installed in case 2 at the current costs, using ϵ-constraint method. The cost of the storage system will be reduced to the point that the storage system will be feasible in energy system.

Case 4 (No storage, RES50): Same as case 1 while considering 50% cost reduction in renewable energy systems. This case is applied to on-grid systems to study the effect of RES capital cost reduction and compare it with operation cost of grid.

Case 5 (Storage system, RES50): Same as Case 2, but the renewable energy cost reduces by 50%. This case is only applied to on-grid systems.

Case 6 (Low cost storage, RES50): Same as Case 3, but with 50% cost reduction for renewable energy systems. This case is only applied to on-grid systems.

3.6 Results

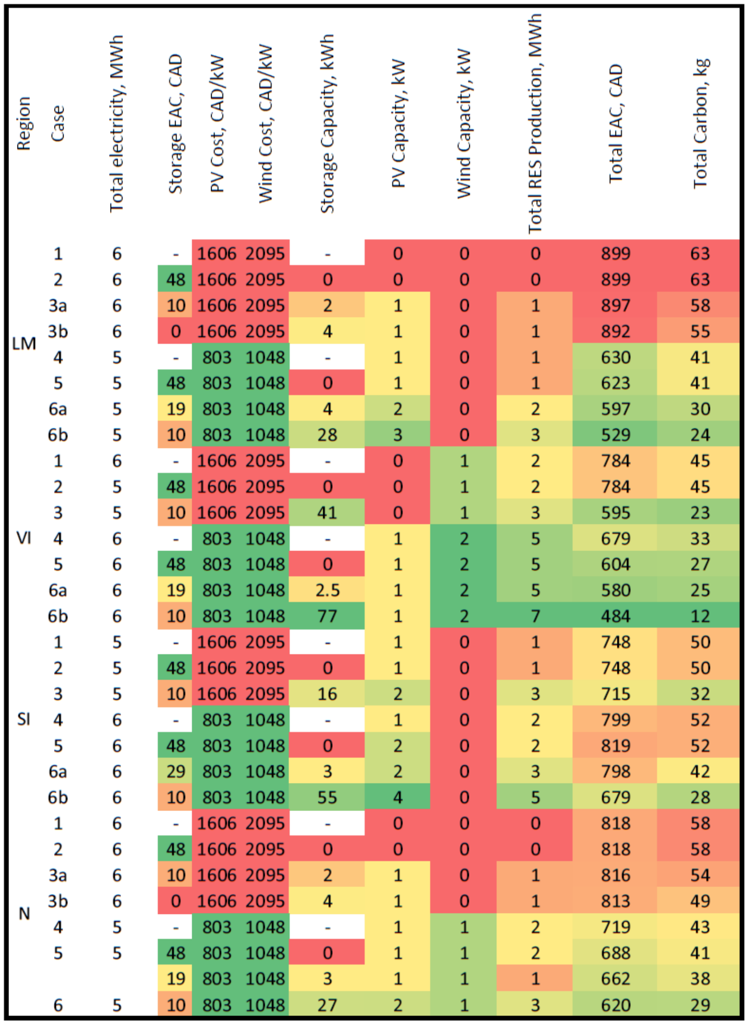
Figures 3.8 to 3.14 show the results of the energy system optimization giving the metrics of total cost, total carbon emissions, the optimal converters capacities and the optimal storage system capacities, as well as the important input parameters that are changing between each case. The static input in different cases are given in scenario description previously.

3.6.1 On-grid systems

Single buildings

Figure 3.8 shows the results for on-grid single buildings for different cases considering different energy model inputs. In this table, "Total electricity" represents average annual electricity demand of single buildings across the random sample of 20 buildings used in analysis. "Storage EAC", "PV Cost" and "Wind Cost" are the inputs of the model corresponding to cases 1 to 6. Results for Pumped hydro are not included in this table since the results show that PH is not feasible for single on-grid buildings. Therefore, the "Storage EAC" column presents the Li-ion EAC.

According to Figure 3.8, energy storage systems are not feasible at the current cost of Li-ion system (48 $CAD) in any regions even at 50% reduction in renewable energy systems cost. At current cost of renewable energy systems, Li-ion is starting to install in energy systems when its cost reaches to 10 CAD/kWh. Assuming minimum Li-ion capacity is 2.5 kWh [23] confirms that storage capacity in Lower mainland and Northern region are very small (2 kWh) which leads the analysis (ϵ-constraint method) to continue and find the feasible cost. Assuming that the storage system is free (similar to net metering), capacity of storage systems increase in these regions to 4 kWh. The impact battery cost reduction in LM and N on total EAC of system is very small and caused 13 to 16 % decrease in total carbon of system. Moreover, Decreasing storage cost to 10 $CAD in VI and SI results in 24% and 4% reduction in total EAC



Region	Case	Total electricity, MWh	Storage EAC, CAD	PV Cost, CAD/kW	Wind Cost, CAD/kW	Storage Capacity, kWh	PV Capacity, kW	Wind Capacity, kW	Total RES Production, MWh	Total EAC, CAD	Total Carbon, kg
LM	1	6	-	1606	2095	-	0	0	0	899	63
	2	6	48	1606	2095	0	0	0	0	899	63
	3a	6	10	1606	2095	2	1	0	1	897	58
	3b	6	0	1606	2095	4	1	0	1	892	55
	4	5	-	803	1048	-	1	0	1	630	41
	5	5	48	803	1048	0	1	0	1	623	41
	6a	5	19	803	1048	4	2	0	2	597	30
	6b	5	10	803	1048	28	3	0	3	529	24
VI	1	6	-	1606	2095	-	0	1	2	784	45
	2	5	48	1606	2095	0	0	1	2	784	45
	3	5	10	1606	2095	41	0	1	3	595	23
	4	6	-	803	1048	-	1	2	5	679	33
	5	6	48	803	1048	0	1	2	5	604	27
	6a	6	19	803	1048	2.5	1	2	5	580	25
	6b	6	10	803	1048	77	1	2	7	484	12
SI	1	5	-	1606	2095	-	1	0	1	748	50
	2	5	48	1606	2095	0	1	0	1	748	50
	3	5	10	1606	2095	16	2	0	3	715	32
	4	6	-	803	1048	-	1	0	2	799	52
	5	6	48	803	1048	0	2	0	2	819	52
	6a	6	29	803	1048	3	2	0	3	798	42
	6b	6	10	803	1048	55	4	0	5	679	28
N	1	6	-	1606	2095	-	0	0	0	818	58
	2	6	48	1606	2095	0	0	0	0	818	58
	3a	6	10	1606	2095	2	1	0	1	816	54
	3b	6	0	1606	2095	4	1	0	1	813	49
	4	5	-	803	1048	-	1	1	2	719	43
	5	5	48	803	1048	0	1	1	2	688	41
			19	803	1048	3	1	1	1	662	38
	6	5	10	803	1048	27	2	1	3	620	29

Figure 3.8: On-grid Single Buildings

and significant decreases of 79% and 36% in total carbon emissions. Therefore, Li-ion battery cost should decrease by 80% to be feasible in VI and SI with the current cost of grid electricity and renewable energy systems. The achievable EAC of Li-ion increases to 29 $CAD/kWh when the capital cost of RES reduces to 50%. It means that at constant cost of 70 CAD/kW of inverter, the storage unit capital cost should decrease to 136 CAD/kWh (which is 50% of the initial storage unit cost). The feasible cost in LM, VI and N is 19 $CAD/kWh.

Districts

The results for district buildings are shown in Figures 3.9 and 3.10. Similar to single buildings, pumped hydro system is not feasible in district buildings, therefore it is not shown in figures. Case 1 and 4 (when there is not storage system) are not shown in this plots since their results are similar to Case 2 and 5. Based on these graphs, Li-ion system is not part of the energy systems at the current cost (Case 2, battery EAC 48 CADkWh). Similar results are happening to energy systems when renewable energy system cost is high and storage system cost is 29 CAD/kWh. All regions install Li-ion when its cost decreases to 10 CAD/kWh.

In district on-grid systems when the total electricity demand of the system increases, energy storage system will be installed in all regions at EAC 10 CAD/kWh (Figure 3.9). EAC of 10 CAD/kWh is possible when the inverter capital cost is 70 CAD/kW and storage unit cost reduces to 0 CAD/kWh. Small storage sizes (1.2-3.7 kWh) are also installed in VI when its cost is 29 CAD/kWh. Interestingly, installation of Li-ion in energy systems do not causes huge differences in total cost of the system. In comparison to small changes in total cost, total carbon of the system is decreasing by 40% and 35% in SI and VI, respectively. Higher renewable energy generation and lower imported energy from grid leads the system to lower carbon emissions. This fact leads the system to buy less energy from grid (lower operation cost), but using this saving as investment cost of renewable systems. Figure 3.10 presents that Li-ion battery is installed at cost of \$29 CAD/kWh in Southern Interior region which causes about 30% reduction in total carbon emissions of the system however the changes in total EAC are negligible.

There is always trade off between annual operation cost of the grid and investment cost of renewable converters and storage systems. The grid electricity is always available for on-grid systems without any limitation. Therefore, even in peak electricity demands there is the guarantee to confirm the energy balance equation. Additionally, the surplus renewable energy can export to grid without any cost. Therefore, with high cost of renewable and storage systems and also low cost BC grid electricity, there is not any feasibility for residential renewable energy systems (RRES) to install in neither individual buildings nor district system. The feasibility of installation of RRES will increase by reducing their cost. This can lead the system to reduce the total cost up to 26% and the total carbon emission up to 62%.

Comparing the results for single buildings and districts shows that total EAC per

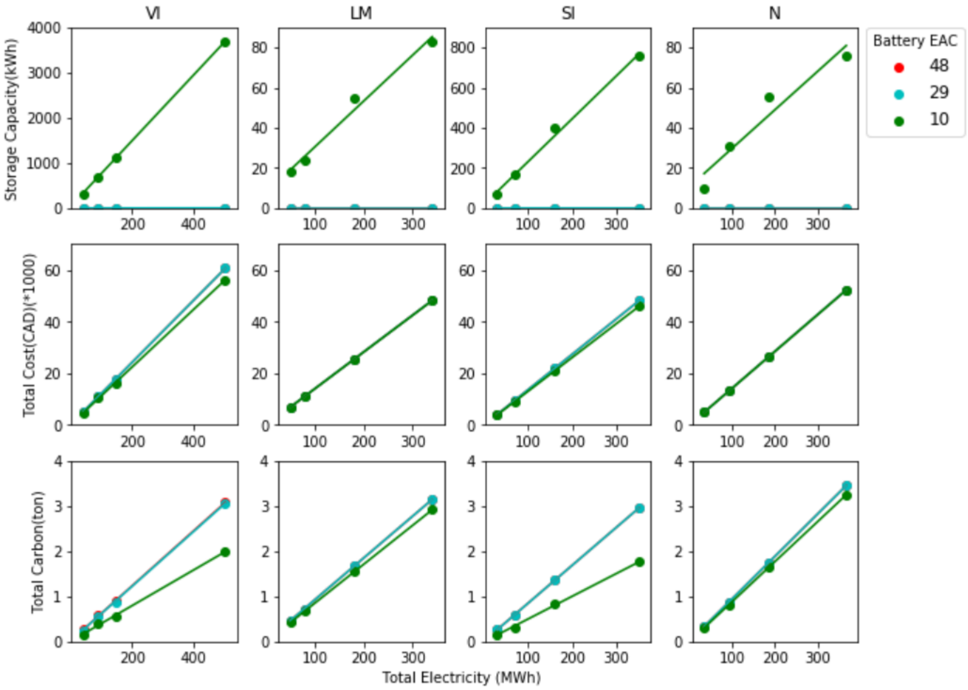


Figure 3.9: Li-ion Capacity in On-grid District Buildings (Case 2,3)

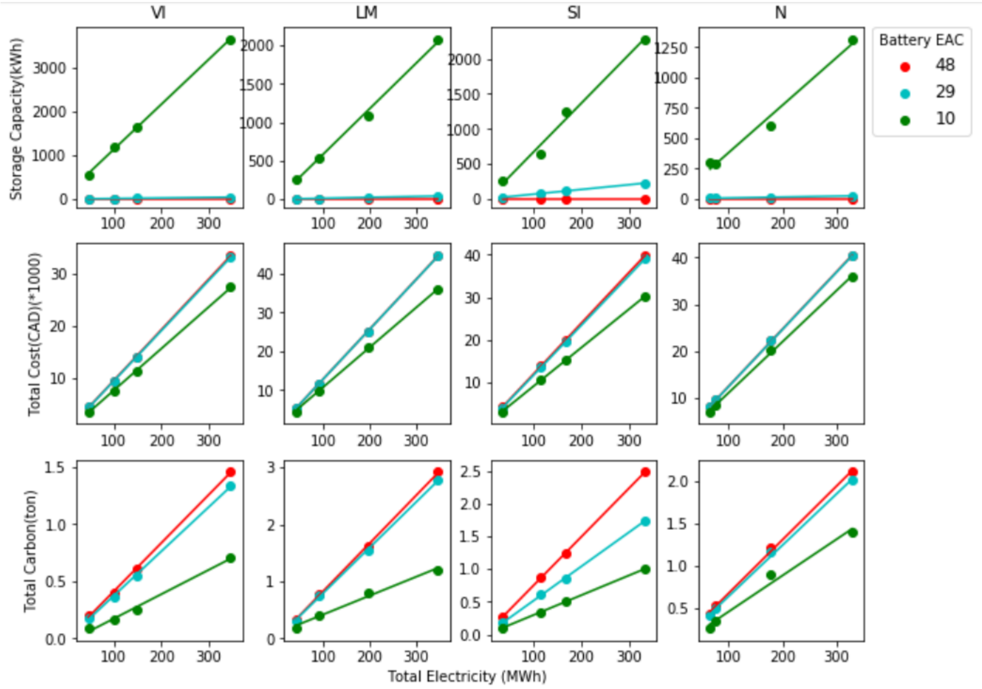


Figure 3.10: Li-ion Capacity in On-grid District Buildings with RES 50% (Case 5,6)

demand (\$CAD/MWh) and total carbon per demand (tonne/MWh) are lower for districts about 5% and 10% respectively. This represents that larger energy systems would benefit more from renewable energy and storage systems which have high capital costs.

3.6.2 Off-grid systems

The results of off-grid system are shown in figures 3.11 and 3.12 for single buildings and district, respectively. The results are shown for Case 1 and Case 2 with Li-ion and PH. According to these figures, both storage systems are available in all regions. When the system turns into off-grid, there is still a guarantee system (diesel generator) similar to grid in on-grid systems but with higher fuel costs and higher carbon emissions. Therefore, the system should choose between high operation cost and carbon emissions, or high RES investment cost and low carbon emissions. According to the results, the system mainly supply its electricity demand using renewable energy sources and storage system but due to the intermittency of renewable sources and storage systems limitations, diesel generator also generates electricity in some time steps specifically peak demands.

According to Figure 3.11, the increase rate of storage capacity and total EAC in LM and SI are similar however total carbon in Li-ion system is lower than PH. This fact mainly is due to higher efficiency of Li-ion systems that more electricity demand are supplied with green energy. In other regions (LM and SI), capacity of PH are higher than Li-ion but total EAC and carbon are similar which is the result of higher intermittency that system tends to store electricity in cheap storage unit as seasonal storage.

In District systems, the capacity of PH is about 6 time higher than Li-ion while the the changes in total cost and total carbon emissions are negligible. Since PH is cheap and renewable generation in VI are high, the system can store more surplus electricity in PH and import to system later which results in buying lower amount of diesel generator and also carbon emissions. In this case, the investment cost of PH would be higher but results in lower operation cost comparing with Li-ion. Moreover, higher availability of RES in VI (Figure 3.5) leads the system to supply the energy using RES which causes lower operation costs in comparison to other regions.

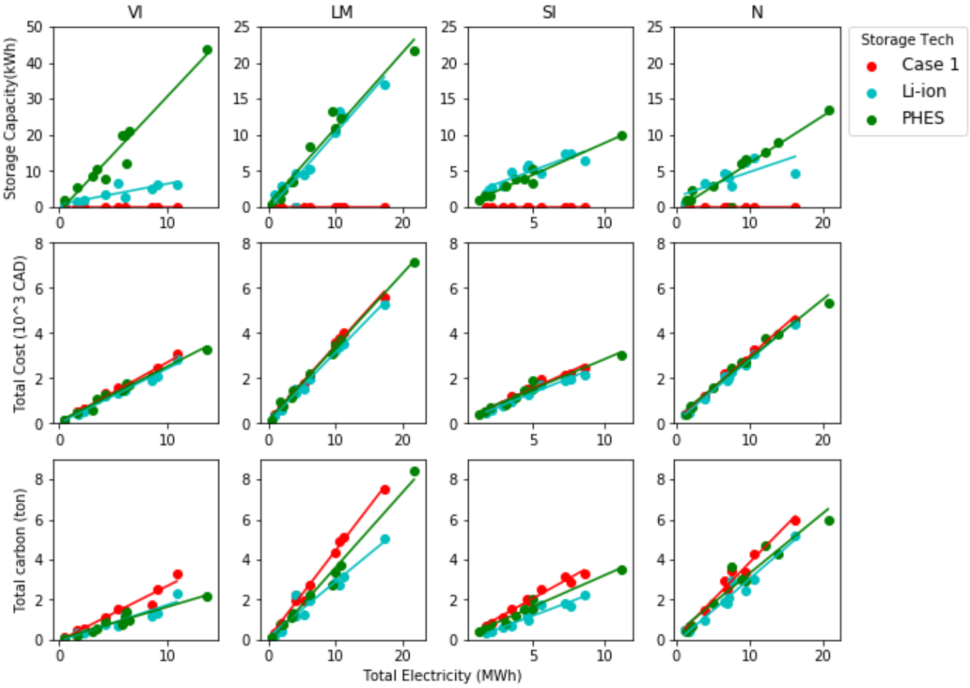


Figure 3.11: Single off-grid buildings

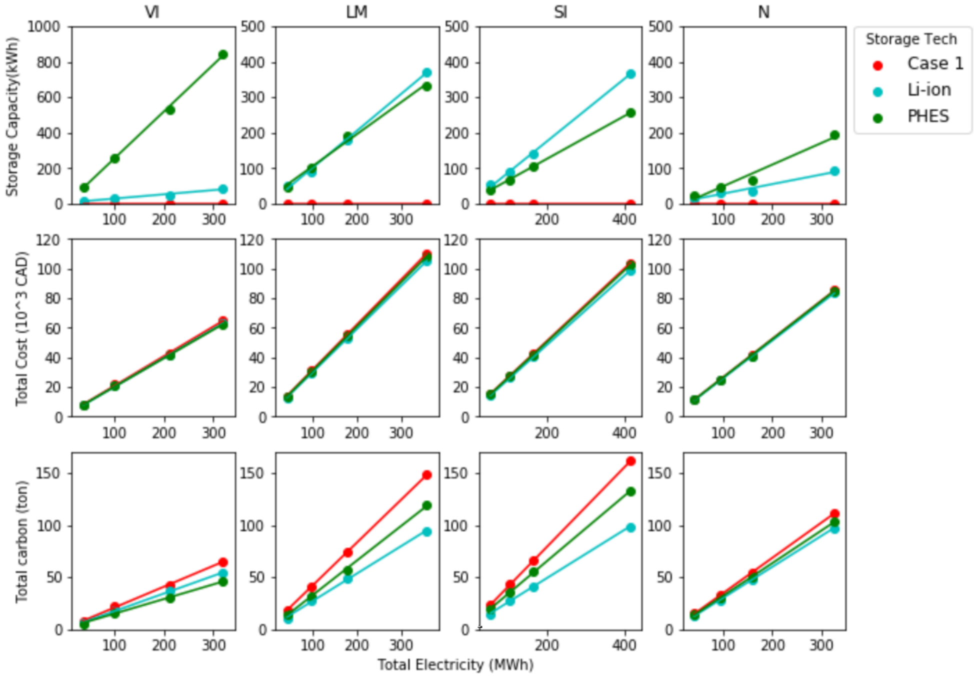


Figure 3.12: District off-grid buildings

3.6.3 Off-grid with 100% renewable systems

In this scenario, there are only renewable energy sources to provide electricity and energy storage system to store surplus electricity. Therefore, total operating cost and total carbon emissions are zero for all buildings. Figures 3.13 and 3.14 indicates the results for single buildings and district buildings respectively.

Despite on-grid and off-grid systems that have a back up system to supply energy whenever energy is not available by RES or in storage system, 100 % green system does not have these immediate systems to supply demand at all time steps. Therefore, energy storage systems role become more impressive. At each time step, system should satisfy energy balance and also should predict future system need to store more energy. This fact results in high storage capacities as well as converters which cause high total cost. According to the results, PH capacity is increasing with higher rate in comparison with Li-ion battery.

Regardless to higher EAC of PH in comparison with Li-ion, the total cost of Li-ion systems are interestingly higher in Northern region and Vancouver Island in comparison to other regions. In these regions, availability of solar energy is lower than Lower Mainland and Southern Interior (Figure 3.5), thus system needs to install more PV panels which results in higher EAC. In this case, higher RES installation is more cost effective for the system than using storing the energy Li-ion battery. In this case, we conclude that lower EAC is not necessarily means that system will choose this system as storage system. Capital cost of storage unit is very important in systems that their mismatch in more seasonal. In these cases, lower storage unit leads the system to store as much as energy needed in high period energy and supply demand when the energy is not available. This gives the chance to system install smaller RES system and store the surplus in cheaper storage units for later use.

The total EAC in Southern Interior for both single buildings and districts is equal. In this case, there would be a trade off between choosing PH and Li-ion battery. In this case, the geographical situation of the location, availability of land for renewable energy systems and maintenance costs (RES, PH and Li-ion) are important factors to choose the energy system.

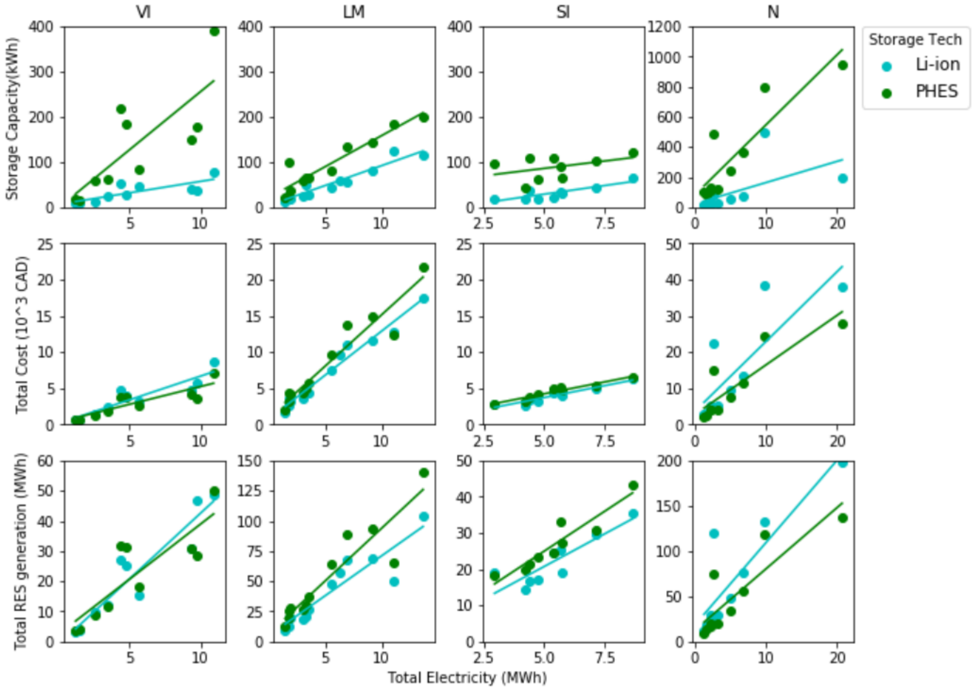


Figure 3.13: Single off-grid buildings with 100% renewable energy

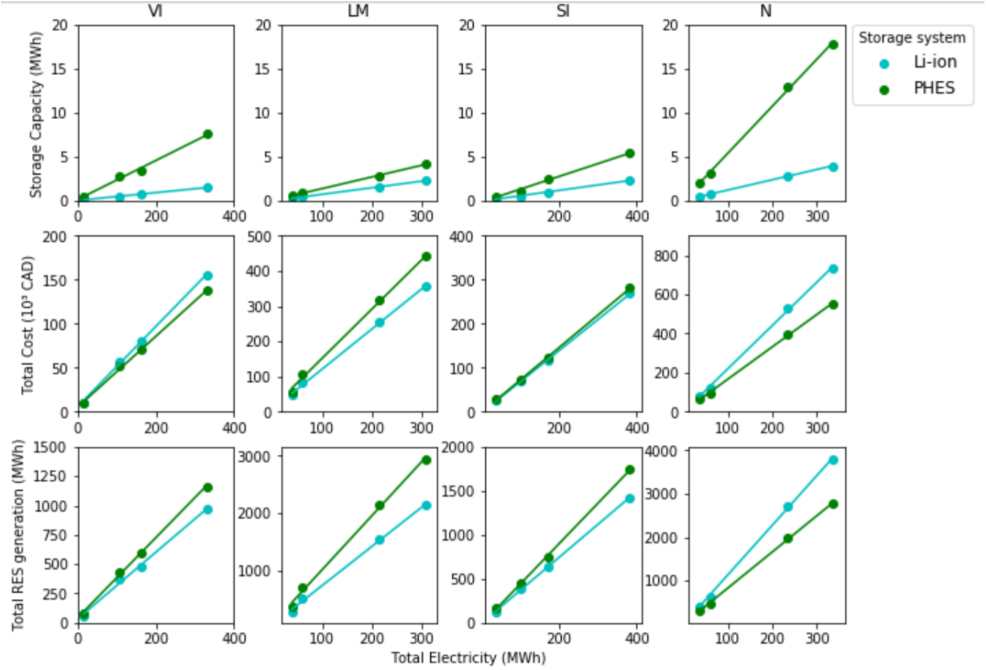


Figure 3.14: District off-grid buildings with 100% renewable energy

3.7 Conclusion

In this research, different storage systems based on their properties are studied. Important characteristics of energy storage systems including capital cost of their inverter and storage unit, lifetime and efficiency are analyzed using equivalent annual cost. A comparison between applicability and cost effectiveness of storage system are studied considering both energy and converter units in storage technologies. In this analysis, we find out that not only the capital cost of storage unit is important as an decision variable but also capital cost of power unit (inverter) is an important decision variable. According to this analysis, we conclude that the most possible storage technologies in residential buildings are Li-ion and PHES. Moreover, various storage systems and their feasibility in different energy systems located in four regions in BC are investigated. Different buildings and districts at varying annual energy use were optimized using the energy hub. System size, carbon emissions and cost trends among the results are found and discussed. For on-grid systems in BC energy system do not install storage technologies due to expensive storage systems and cheap grid electricity. Decreasing capital cost of renewable energy systems, storage technology or both result in higher storage installation, lower cost and lower carbon emissions. In both off-grid and off-grid with 100% RES, storage systems (Li-ion and PHES) are installed in most of energy systems as results of high diesel fuel cost and intermittency of renewable energy sources. There is always trade off between installing Li-ion and PHES in the system since Li-ion EAC is lower and good when the system needs more peak shaving. In addition, in energy systems with seasonal changes in generated renewable energy PH is more feasible due to its low energy unit costs ($6.5 CAD/kWh).

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Chapter 4

Assessing simple methods of sizing energy supply and storage systems for off-grid communities

Prepared for submission to Applied Energy journal

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4.1 Abstract

Supplying energy in off-grid remote communities in Canada is a challenge due to high cost of fossil fuels (typically diesel for generators) and their high environmental impact. The mismatch between renewable energy and demand requires energy storage technologies or dispatchable energy sources. Since dispatchable energy sources are high in carbon emissions and storage technologies are expensive, there is a trade off between system cost and carbon emissions. In this paper, various factors methods of energy systems sizing are studied. These factors leads off-grid communities to a wide range of scenarios to choose the best energy system based on their priorities and limitations.

4.2 Introduction

Taking action against climate change requires us to mitigate global CO_2 emissions in the electricity sector by moving toward renewable energy sources (RES) over the next years. The government of Canada committed to reduce greenhouse gas emissions by 30% (according to 2005 level) by 2030 [4]. To achieve this target, new emissions standards are defined to decrease the reliance of remote communities on diesel generation [2]. 257 of 292 Canadian remote communities are off-grid and powered by diesel generators [25]. There are economic and environmental impacts on these communities(nearly 220,000 residents) due to reliance on diesel fuel for energy generation. Fuel is delivered by air, water or road which results in very expensive diesel fuel and large amounts of carbon emissions due to transportation. Moreover, the cost of power is affected by generator properties (efficiency, size, lifetime, etc) and operation and maintenance (O&M) costs. The health and environmental impacts of diesel generators cost between \$0.03 CAD to 0.19 per kWh of diesel generated electricity [3]. Environmental issues and expensive fuel costs suggest that alternative energy solutions should replace current energy systems to improve energy sustainability in these communities.

In order to address various issues concerning electricity generation in remote communities, deployment of renewable energy sources must be investigated to assess the feasibility of environmentally friendly and cost effective solutions to meet electricity demands in remote communities [2]. Shifting to renewable energy sources wind and solar causes significant challenges as they fluctuate over time and have high initial costs. Since solar energy and wind energy are variable, high levels of energy supply can be challenging to integrate into energy systems. The variability of renewable energy sources depends on weather conditions, location, time of day and season [9]. Maintaining a system energy balance is the key factor in ensuring that the supply meets demand at all times. The potential mismatch of demand and supply means we have to find solutions to deal with situations when there is surplus energy generation and also when the demand is higher than the energy generation [15]. Energy storage technologies are one solution to supply-demand mismatch that allow the system to shift energy over time. Integrating storage system with renewable energy systems rise the question of how much of the excessive renewable energy should be stored. There are two extreme cases in which all surplus energy is stored (maximum size of storage) or none is stored. Typically, there should be an efficient size in between that can store some amount of surplus renewable energy; the rest must be curtailed. In addition, increasing the share of renewable energy sources increases storage capacities non-linearly [26]. Therefore, aiming to size storage systems which store all surplus energy without curtailment leads to very high storage capacities [27]. Consequently, the optimal solution for each energy system highly depends on energy demand, renewable energy profiles, the share of renewable energy sources and etc. In this paper, we study various ways to design off-grid energy systems to find the impact of different factors in these systems.

There are always challenges in designing renewable energy systems in off-grid remote communities. Lack of energy demand data, specifically hourly data, is a major main challenge. Due to daily and seasonal changes in renewable sources, designing a reliable energy system needs hourly data to calculate the mismatch between energy generation and energy demand. Therefore, we analyze different demand profile results and comparing them with original demand results to find the reliability of these systems.

4.2.1 Literature review

There is a wide literature background to design and analysis of energy systems using optimization. We mainly focus on renewable energy system designs and their optimization methods. Additionally, previous researches in remote communities are taken into account. Various researches have been addressed the integration of different renewable energy and storage system. Analysis on the demand and supply require various energy models with focus on climate policies, economic development and energy security [22]. This research mainly focus on energy policy models to address the model challenges including energy system transition, uncertainties and social risks. In energy model design, it is important to take into account the economic and regulatory challenges of deployment of variable renewable energy sources [18]. This research focuses on short term and long term security of energy supply in renewable energy sources to fulfill energy balance and and flexibility in energy system. The mismatch between demand and renewable energy generation increase the energy curtailment in the system which highlight the importance of energy storage availability in these energy systems. Integration of storage system to store all surplus energy unreasonably increases storage capacities which is not beneficial most of the time [26]. Further researches indicate that optimization models can optimally combine renewable sources with storage system with certain level of energy curtailment [28]. A cost optimization model is presented in [17] to handle electric and thermal loads at different scales. There are several publications on communities energy systems which are based on the "energy hub" model. This model explains an energy system that multiple energy inputs are converted to satisfy multiple energy outputs [13]. In this research, they use a mixed integer linear programming (MILP) to find the energy converters and energy storage systems integration. The application of energy hub in different scenarios including various energy carriers is studied to schedule various appliances and storage components [7]. The use of energy hub in decentralized neighborhood considering application of short-term and long-term storage systems indicate that to handle high surplus energy in energy system integration of long-term storage systems are beneficial [19]. Moreover, this research illustrate that in low surplus systems short term storage systems are the best options for effective load shifting. Previous works in energy hub are commonly use typical days instead of full hourly annual optimization. This have minimal impact on accuracy and reduces the run time, but makes it harder to formulate seasonal energy storage.

Different aspects of developing new energy systems are studied for remote communities in Canada in few researches [8], [14], [16]. The impact of deployment renewable energy sources on carbon emissions in Northern Ontario can reduce the GHG emissions by 3.5 % without energy storage and bu 6.2% with storage systems [16]. An economic method is studied to reduce system diesel generation by implementing of various energy systems increases the project's present value by 20% in BC [8].

4.2.2 This paper

This paper presents a comparison of methods of analysis of the energy system options available for off-grid remote communities. We study the different challenges in sizing energy systems which must balance accuracy against complexity and data availability. The novel contributions of this study are:

- Analysis of a range of low carbon scenarios for two remote communities using hourly data.
- Assessment of energy storage utilization and renewable energy curtailment.
- Examination of the various decision-making factors in renewable and storage system sizing.

- Comparison of approximate methods of sizing with optimal results obtained from optimizations at hourly resolution

The sections of this research are as following: In next section, the implemented methods in this research are discussed which starts with explaining energy hub model and followed by energy curtailment and approximate demand data. In section 4, we will explain case studies following by energy demands, renewable availability and cost data. In section 5, the results of the research are discussed.

4.3 Methods

4.3.1 Energy Hub model

There is always a trade off between minimizing energy curtailment and minimizing cost of an energy system. Minimizing the cost in this case is a factor of energy curtailment level which leads to fuel purchase, cost of energy storage and cost of conventional technologies. To find the optimal sizes of the energy storage systems and back up technology (diesel generator in this research), we use the "energy hub" model. The energy hub model optimizes the energy flow within a building, neighborhood, city or larger system [12]. Within the energy hub, it is possible to convert various energy carriers (for example diesel fuel to electricity, solar energy to electricity, etc.), store energy between time steps and supply energy (for example electricity, heating, cooling, etc) to meet demands. The main purpose of the energy hub model is to optimize cost, emissions etc by both balancing energy flows and sizing system components [20]. The basic concept of energy hub consist of multiple inputs to be converted in hub to multiple outputs [12][13]. A version of energy hub including storage systems is implemented in [21].

The energy hub related energy inputs I to energy outputs L by a conversion matrix C (Equation 4.1). In this equation, $Q_{ch}(t)$ and $Q_{dis}(t)$ are the energy send to storage and discharge energy from storage, respectively. e_{ch} and e_{dis} are the efficiency of charge and discharge in storage system. This equation is the most important equation in energy hub which is energy balance equation. The main purpose in energy hub model is to minimize one or more objective functions, shown in equation 4.2. F is a vector a input coefficients like capital cost (minimize investment cost), operating cost (minimize operation cost) and etc. Based on the model, different constrains for the system are defined, equation 4.3, 4.4. Equation 4.3 shows the limitations in availability of input, for example from solar energy. Equation 4.4 shows the limitations on minimum and maximum capacity of converters.

$$L = C \times I - e_{ch}Q_{ch}(t) + e_{dis}Q_{dis}(t) \tag{4.1}$$

$$minM = F \times I \tag{4.2}$$

$$I \leq I_{max} \tag{4.3}$$

$$P_{min} \leq P \leq P_{max} \tag{4.4}$$

In Figure 4.1, the energy hub model implemented in this paper is presented. A comprehensive description of the model can be found in [10]. In this model, there are three energy converters PV panels, wind turbine and diesel generator. Surplus renewable energy can be stored in the energy storage and used in the system at a later time. The model has the freedom to store a certain amount of surplus renewable energy and curtail rest (equation 4.5). According to this equation, the generated renewable energy at each time step is equal to the portion used to meet demand ($P(t)_{RES,elec}$) plus energy delivered to the storage ($P(t)_{RES,ch}$) and curtailed energy ($P(t)_{RES,cur}$). The objective function of energy hub is minimizing the equivalent annual cost (EAC) of the capital costs of all converters and storage systems added with annual operation cost. More details are available in section 3.4.1 .

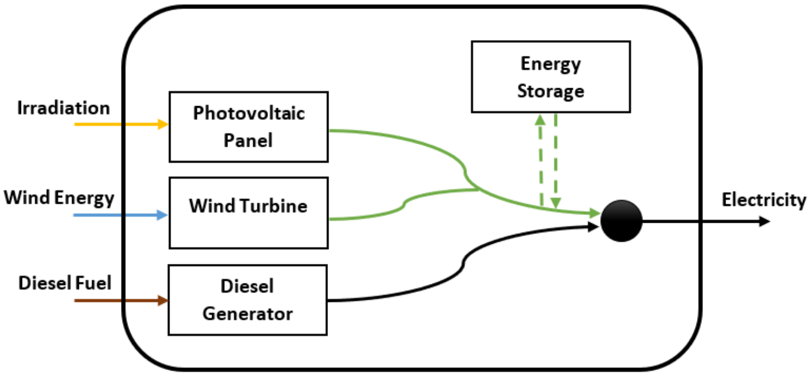


Figure 4.1: Energy hub model, (Energy storage system is only connected to renewable energy streams)

$$P(t)_{RES,gen} = P(t)_{RES,elec} + P(t)_{RES,ch} + P(t)_{RES,cur} \tag{4.5}$$

4.3.2 Energy curtailment and effective RES

Energy curtailment is defined as wasted renewable energy when the demand is higher than the generated renewable energy and excess production can not be exported or stored. To illustrate the variability energy curtailment by shares of variable renewable energy electricity. Residual load duration curves are plotted for both locations. Different shares of renewable energy are defined according to total demand. For example, 10% renewable energy means that total renewable energy generation is 10% of total demand. The residual load duration curve has two sections: the positive side and negative side. The positive side represents hours with high demand when renewable energy do not meet the demand. The negative side indicates curtailment of renewables when the demand is lower than renewable generation. The negative side also show the maximum useful storage capacity of storage system.

Different shares of renewable energy (10%, 50%, 90% and 100%)are considered, and we calculate energy curtailments of each case. The results are compared with optimal solutions of storage technologies.

Effective RES defines the share of effective renewable energy that supply demand. In other word, it is the efficient share of renewable energy (excluding system losses and curtailments) that supply demand.

4.3.3 Approximate demand data

Since hourly data are rarely available in remote communities, two very approximate demand profiles are analyzed. First, a constant equal to the average annual energy demand of the community is analyzed. Second, a constant value for each month is calculated to reflect seasonal trends which might be available . These cases are studied since access to annual and monthly data is easier than hourly data, e.g. annual data are available from Natural Resource Canada [1]. Using average demand data when there is lack of hourly data would be helpful, but will impact the accuracy of the results . Therefore, we study the impact of using approximate demand data. The demand profiles are presented in Figure 4.2. In this demand profiles, all daily fluctuations are ignored.

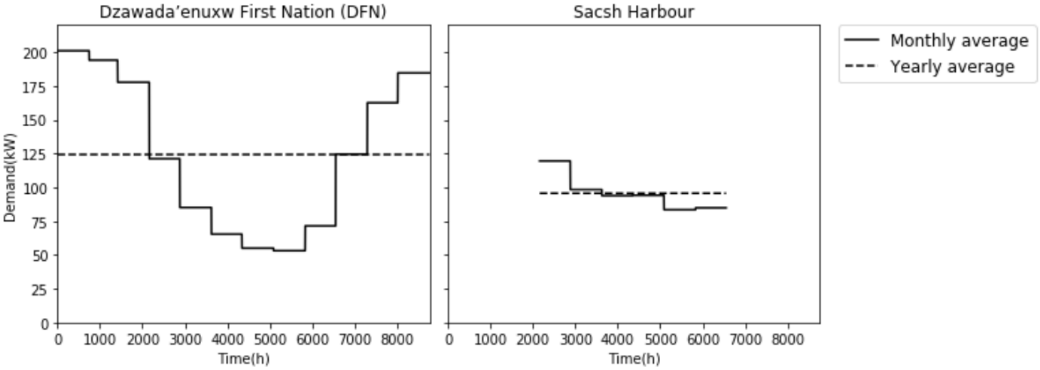


Figure 4.2: Approximate demand data using the annual average and monthly average demands

4.4 Case studies

4.4.1 Energy demands

We have access to high residential demand profiles in British Columbia (BC) and in the Northwest territories(NWT) in Canada. Table 4.1 presents the information on these communities. Both communities use diesel to supply their demands. Both do not have access by road all over the year. In addition, DFN does not have air access. Both data contain 15 minute time intervals, although we use hourly intervals in this work. Data from Sachs Harbour were missed which leads the research to analyze only from April to September. For single missing data, the average demand before and after the missing hour is used. The hourly demands of both communities are shown in Figure 4.3.

Table 4.1: Community information [1]

Name	Province	Year-round road	Fly-in	Population	Main power source
Sachs Harbour(SH)	NT	No	Yes	103	Diesel
Dzawada'enuxw First Nation(DFN)	BC	No	No	91	Diesel

4.4.2 Renewable availability

Renewable energy time series are obtained from the open source platform "Renewables.ninja" [23]. For solar power, a single photovoltaic panel capacity of 1 kW, system loss of 0.8, tilt angle of 35 and azimuth angle of 190 are considered for both locations. Hourly wind power is calculated considering on example turbine model of

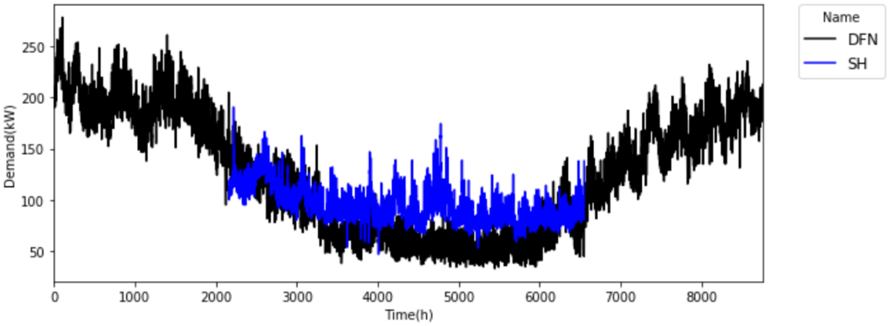


Figure 4.3: Hourly energy demand data. Black:DFN, Blue: SH from April to September

”Vestas V100 1.8MW” with hub height of 80 meter. Wind power capacity is also normalized for 1kW capacity. Figure 4.4 shows solar and wind power available for both communities. In DFN, total solar energy is 259 kWh/kW_p per year and wind energy generation is 602 kWh/kW_p per year. During the period of six months, solar and wind energy generation are 190 and 1488 kWh/kW_p per year, respectively.

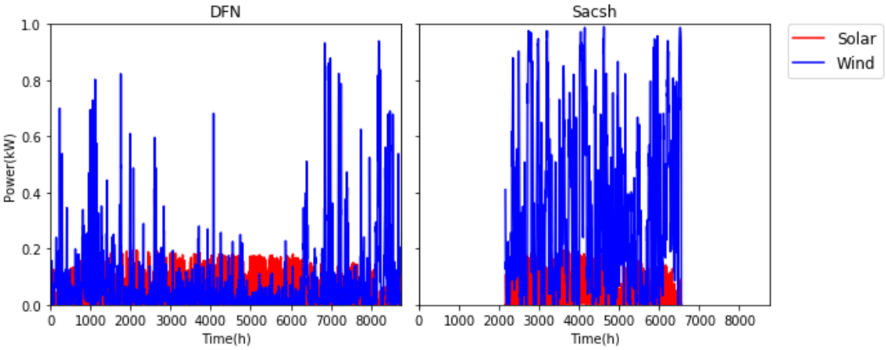


Figure 4.4: Solar power (red) and wind power (blue). Right: Sacsh

4.4.3 Cost data

The cost data required to analyze the energy systems are given in this section. The diesel fuel cost in DFN is \$CAD1.21/L and in Sachs Harbour is \$CAD0.052/L [1]. Additionally, it is assumed that communities spend \$CAD2.22/L for operation and maintenance (O&M) costs. Therefore, total cost of diesel fuel is \$CAD2.272/L and \$CAD3.43/L in Sachs harbour and DFN, respectively. The characteristics of energy converter and storage technologies are presented in Table 4.2. The energy efficiency of PV and wind turbine are considered to be 100% as their efficiencies are already in applied by "Renewable.ninja". The carbon tax is assumed to be $CAD40/tonne.

Table 4.2: Energy converter and storage system Characteristics and costs

Technology	Efficiency (%)	Energy Capital Cost ($CAD/kWh)	Power Capital Cost ($CAD/kW)	Lifetime (year)
PV[24]	100	-	1606	25
Wind Turbine[24]	100	-	2095	25
Diesel Generator	40	-	325	30
Li-ion battery[11][6]	85	272	91	11
Pumped Hydro Energy Storage (PH)[5]	75	6.5	2600	40

4.5 scenarios

As discussed, remote off-grid communities are based on diesel generator and usually the annual demand of community is the only number available from community. As a result, the easiest way to design new new energy system is to size renewable energy systems as a percentage of annual demand. Therefore, in first step different shares of renewable energy are considered to mimic how renewables are sized in reality. Secondly, we add storage to same cases to study the changes of the system by adding energy storage technologies. These cases are compared with base case (diesel only), optimal design and 100% renewable system. In optimal scenario, renewable energy converters (PV and wind turbine), storage technologies (battery and pumped hydro) and diesel generator are optimized. 100% renewable scenario is the same as optimal scenario but it exclude diesel generator.

4.6 Results and discussion

Figures 4.5 and 4.7 show the results of the analysis for each PV, wind and mix of PV and wind, percentage of renewable energy and availability of energy storage system. For example, ESS_PV10 represents the scenario in which energy storage is used, generation is from PV and the share of annual solar energy compared with annual demand is 10%. In "Mix" scenarios, both PV and wind turbine are converters in energy system with equal annual energy generation and the number implement sum of annual solar and wind energy.

Figure 4.5 shows renewable energy curtailment and effective RES for both communities. For scenarios with 10% share of renewable energy, energy curtailment is

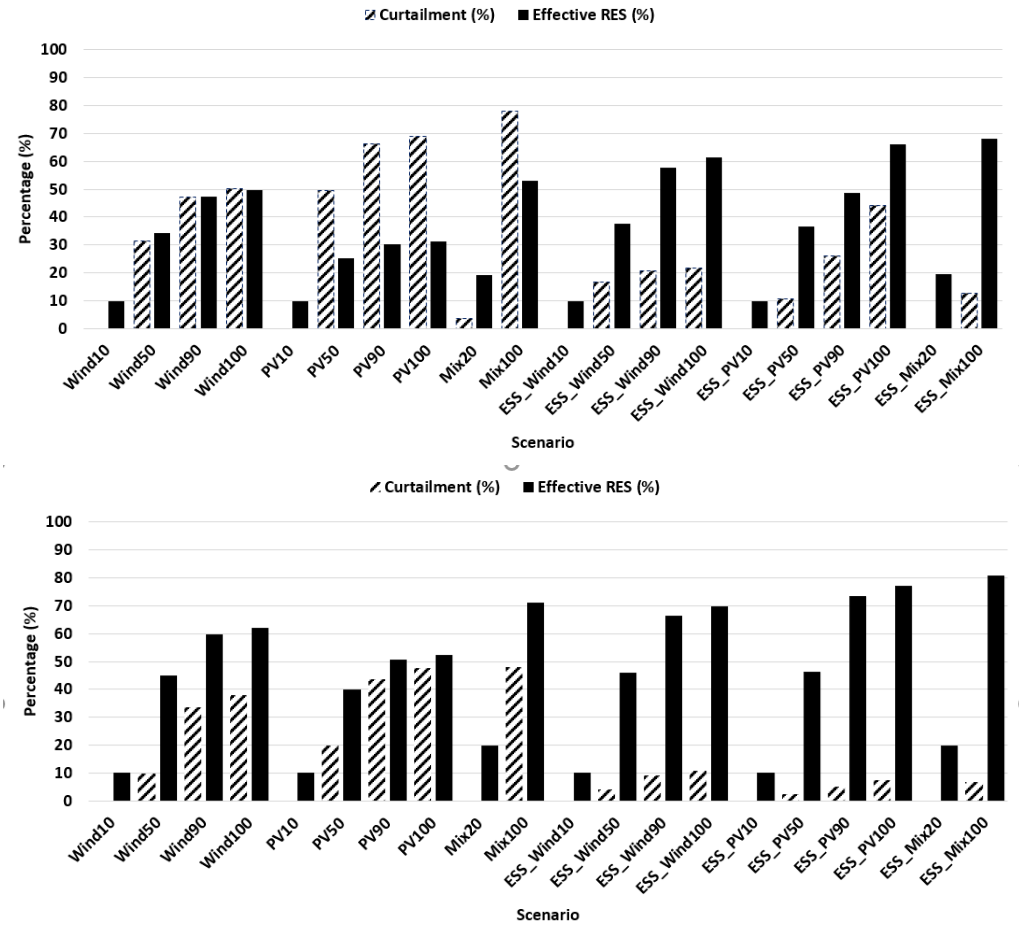


Figure 4.5: Energy curtailment and effective renewable energy.(Up: DFN.; Down: Sachs harbour)

zero. Curtailment increases when the share of renewable energy increases. The energy curtailment results show that energy curtailment in most solutions is not zero. Zero curtailment only happens when the share of renewable energy is 10% of annual demand, because hourly energy generation is always smaller than hourly energy demand. The energy curtailment in both communities increases when renewable energy generation increases, however the rate of growth is not linear. Adding storage technologies to energy systems results in energy curtailment of lower than 10% in Sachs Harbour. Effective RES is a factor of system efficiency and energy curtailments. For equal shares of renewable energy, the effective RES is higher for wind systems compared to solar systems, and higher again for mixed systems. This is due to lower mismatch between demand profile and wind profile.

Residual load duration curve are presented in Figure 4.6. The black lines in this

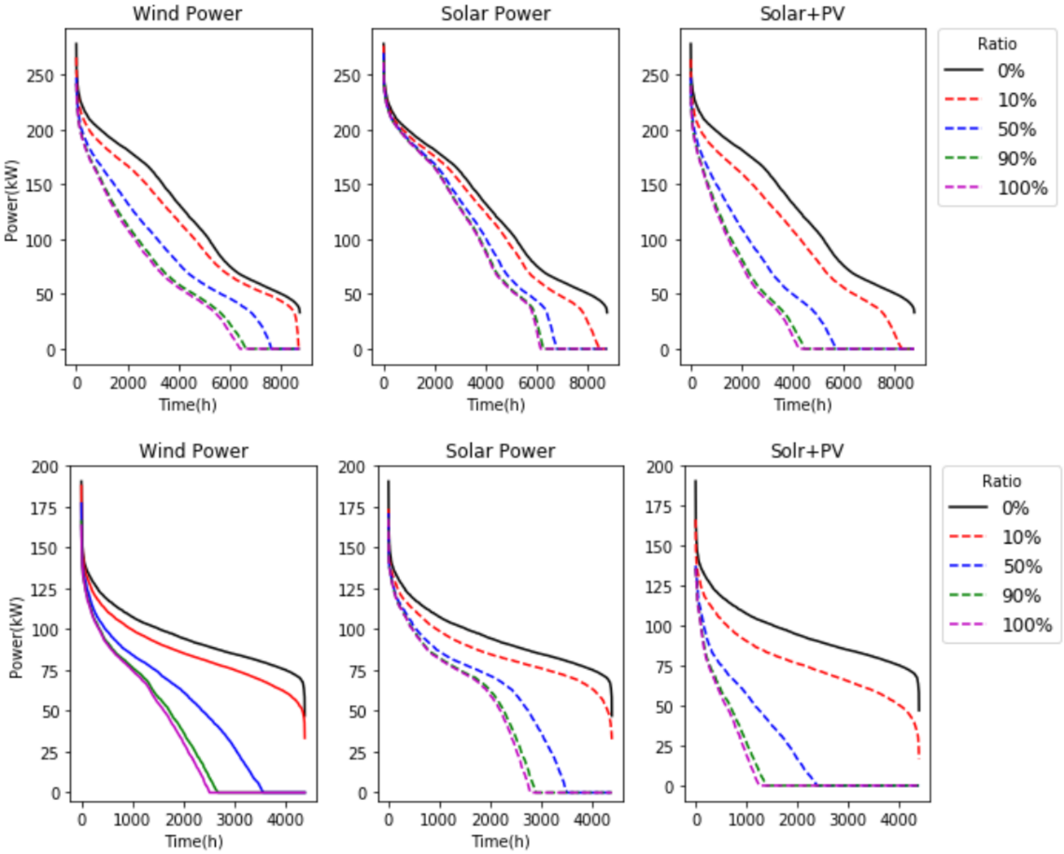


Figure 4.6: Residual load duration curve considering energy curtailments (The lines with zero value presents the time steps that energy curtailed) .(Up: DFN.; Down: Sachs harbour)

plots show the demand duration curve of the demand while the colored lines present the residual load demand of different shares of RES when surplus energy curtailed (zero lines). According to this plot, the curtailment increases when the share of renewable energy is higher.

Figure 4.7 shows the equivalent annual cost of all converters and storage systems that are available in each energy system as well as annual operation cost of the diesel generator in k$CAD on the left axis. Right axis illustrates the total carbon emissions of each system in tonnes of emitted CO_2. Moreover, the numbers at the end scenario represent the payback time of each system. In all cases, the size of renewable energy converters are determined in advance, then used by the energy hub model to size the other components. Additionally, a base case scenario is shown in both figures which represents the current situation in each community, where there is only a diesel generator. Therefore, the EAC axis shows the investment EAC of the diesel

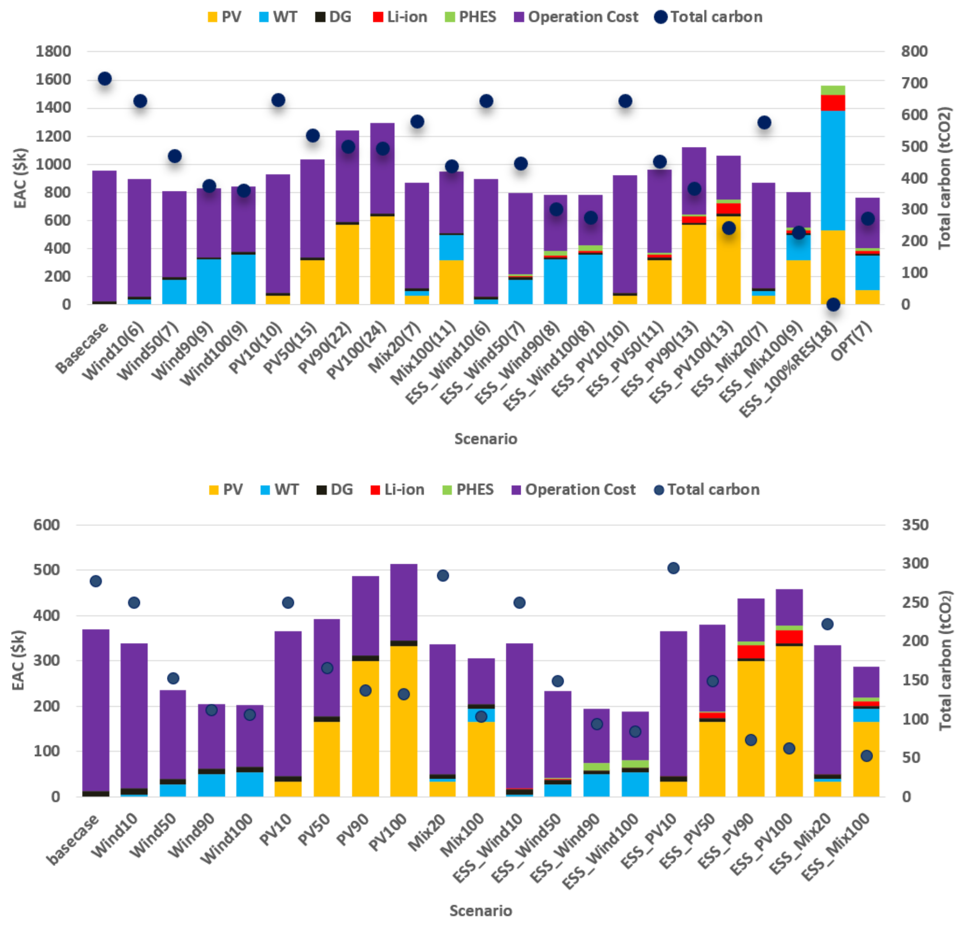


Figure 4.7: Cost breakdowns for all scenarios. The left axis gives EAC (k\$CAD), and Right axis gives Total carbon emissions (tonneCO_2), shown by the blue marker.(Up: DFN.; Down: Sachs harbour)

generator (in black) and the annual operation cost of diesel (in purple). Total EAC and carbon emissions both decrease when storage technologies are available. The decrease in carbon emission is a result of higher effective RES which results in lower diesel generator operation and have lower costs and carbon emissions. Interestingly, the EAC reduces in the ESS_Wind system when the renewable shares increases. In addition, the optimal scenario has the lowest EAC but the payback time is higher than the Wind10 scenario in DFN. This happens since the investment cost of optimal scenario is higher than Wind10. Therefore, a combination of factors determine the best scenario for each community. It is fair to say that there is not a single best solution. For example, if investment capital is limited, the scenario with lowest capital cost will be the best solution. However, it is possible that the annual operation cost and payback time in these scenarios would be higher. In addition to economic and environmental constraints, geographical (for example appropriate location for pumped hydro) and installation (for example accessibility for renewables installation) limitations have to be considered.

The payback time of each scenario according to the savings in diesel fuel is shown. The results for DFN shows that total annual equivalent cost of the optimal scenario is about 800,000$CAD with a payback time of 7 years.

Sankey diagrams of the energy flows in the optimal scenarios for each community are illustrated in Figure 4.8. In both communities, about 48% of total input energy (renewable sources and diesel fuel) are wasted due to system losses or curtailment. Diesel losses are due to the low efficiency of diesel generator. Renewable energy loses illustrated in this figure represents the losses in energy storage systems.

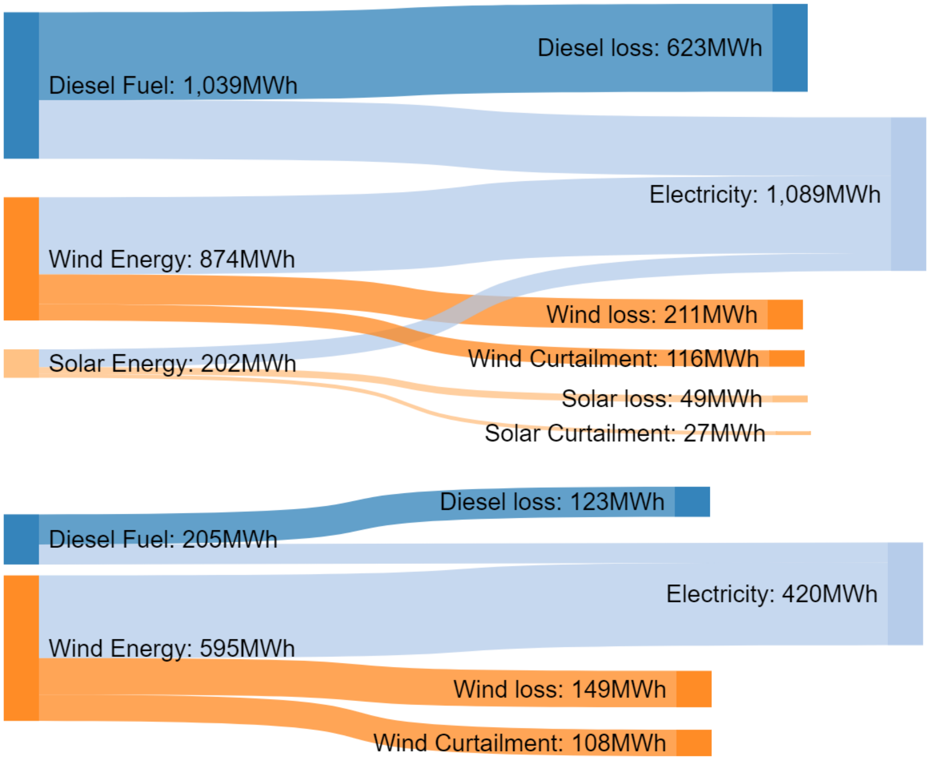
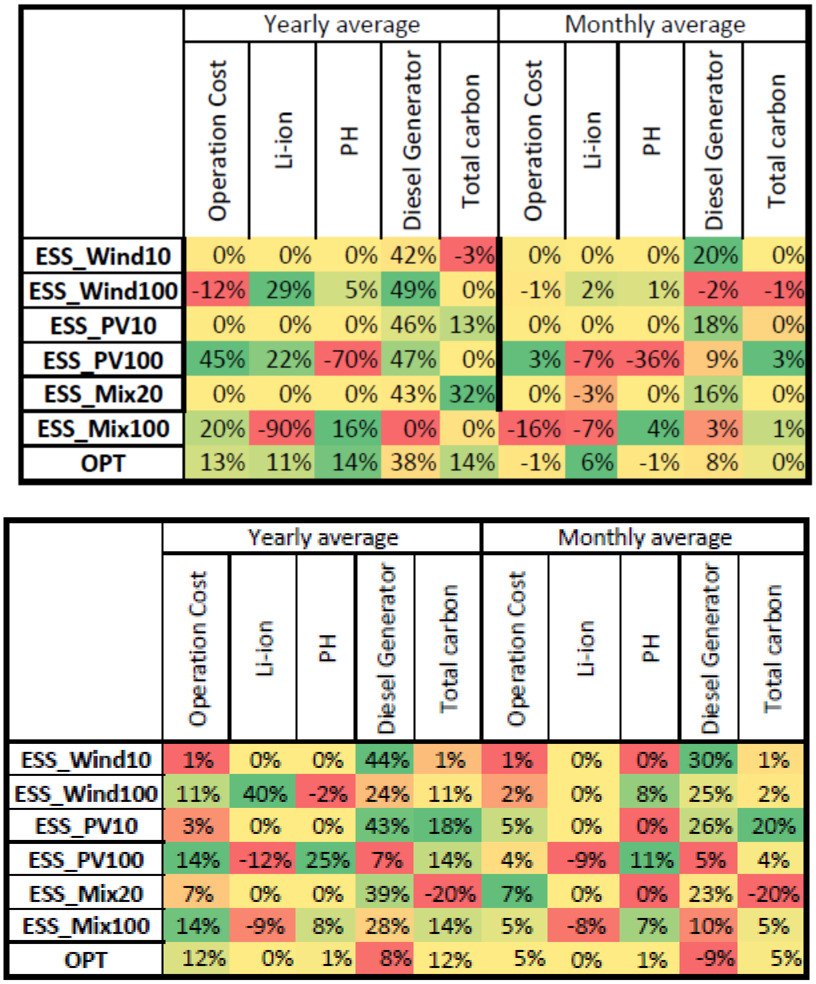


Figure 4.8: Sankey diagram showing energy flows for the optimal scenario.(Up: DFN.; Down: Sachs harbour)

Figure 4.9 shows the percentage change for two cases (yearly average and monthly average) compared with the case uses hourly data. The results shows the changes in converter and storage sizes, operation costs and total carbon emissions of all scenarios.



	Yearly average					Monthly average				
	Operation Cost	Li-ion	PH	Diesel Generator	Total carbon	Operation Cost	Li-ion	PH	Diesel Generator	Total carbon
ESS_Wind10	0%	0%	0%	42%	-3%	0%	0%	0%	20%	0%
ESS_Wind100	-12%	29%	5%	49%	0%	-1%	2%	1%	-2%	-1%
ESS_PV10	0%	0%	0%	46%	13%	0%	0%	0%	18%	0%
ESS_PV100	45%	22%	-70%	47%	0%	3%	-7%	-36%	9%	3%
ESS_Mix20	0%	0%	0%	43%	32%	0%	-3%	0%	16%	0%
ESS_Mix100	20%	-90%	16%	0%	0%	-16%	-7%	4%	3%	1%
OPT	13%	11%	14%	38%	14%	-1%	6%	-1%	8%	0%

	Yearly average					Monthly average				
	Operation Cost	Li-ion	PH	Diesel Generator	Total carbon	Operation Cost	Li-ion	PH	Diesel Generator	Total carbon
ESS_Wind10	1%	0%	0%	44%	1%	1%	0%	0%	30%	1%
ESS_Wind100	11%	40%	-2%	24%	11%	2%	0%	8%	25%	2%
ESS_PV10	3%	0%	0%	43%	18%	5%	0%	0%	26%	20%
ESS_PV100	14%	-12%	25%	7%	14%	4%	-9%	11%	5%	4%
ESS_Mix20	7%	0%	0%	39%	-20%	7%	0%	0%	23%	-20%
ESS_Mix100	14%	-9%	8%	28%	14%	5%	-8%	7%	10%	5%
OPT	12%	0%	1%	8%	12%	5%	0%	1%	-9%	5%

Figure 4.9: Percentage change for yearly average and monthly average compared with the case uses hourly data. (Up: DFN.; Down: Sachs harbour)

The changes of PV panels and wind turbine for optimal scenarios are not shown in these tables. For DFN yearly average, PV panels and wind turbine changes are -98% and 22% and for monthly average, these changes are 2% and -1%, respectively. In Sachs harbour, PV panels do not install in any cases but wind turbine for yearly average and monthly average changes by the rate of -41% and -18%, respectively. Other scenarios show that rate of changes in monthly average scenario are very lower than yearly average. The highest differences belong to diesel generator which is the results of ignoring hourly changes of demand. This can make problems for the system to supply the demand for time steps with high diesel generation since the diesel generator are smaller in size for all cases except ESS_Mix100 (negative value). Excluding diesel generator, the changes of other converters and storage systems are between 0 to 25 %. As result, monthly average demands are more reliable than yearly average when it comes to optimal design of the system. However, it is difficult to extend this conclusion. Using these approximate demand can be useful to find approximate size of renewable energy systems and storage technologies and then to maintain the energy balance of the system using diesel generator as backup. In this case, diesel generator size should be bigger (up to 20% base on Figure 4.9) than what model calculate. In future work, considering daily seasonal profile based on annual demand can be helpful to improve the model.

4.7 Conclusion

In this research, various scenarios for two remote off-grid communities energy systems are studied. The results show that adding storage technologies to system have many impacts on energy system including energy curtailments, cost and carbon emissions reduction. Moreover, the results illustrate that initial investment cost of renewables, annual operation cost of diesel, payback time, level of carbon emissions reduction are the most important factors to choose the best energy system for each communities. We also analyze the yearly average and monthly average demand profiles to study the reliability of these profile since the hourly data are not always available in communities. We find out the monthly average profiles can be more reliable with maximum 25% error.

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Chapter 5

Conclusion

5.1 Conclusion

The goal of this thesis is to investigate the feasibility of energy storage systems in different energy systems using an optimization model. To achieve this goal, different energy systems scales from single buildings to districts and communities are studied. Moreover, "Energy hub" is used to minimize the cost of the energy system as well as find the optimal sizes of different component in system and total carbon emissions. Using hourly energy profiles in this work helps the system reliability to find hourly energy flow in system. More importantly, the model can analysis seasonal storage systems.

In second chapter, the analysis are done for a single off-grid buildings where the hourly data are calculated in EnergyPlus. In this chapter, the effect of diesel price on optimal sizing of energy systems is studied considering for scenarios. The scenarios consider the cost changes in diesel fuel cost, renewable energy system (PV panels) and storage technology. The results shows that hybrid energy systems are cheaper than base case using a diesel generator. The results are illustrated by using contour plots to show the impact these discussed variables.

In third chapter, different properties of storage systems are studied and compared based their specific characteristics. The review of storage systems illustrate that all components of energy storage system including storage unit and converter unit should take into account. The results from this comparison show that Li-ion battery and pumped hydro can be the best options in terms of cost, lifetime and efficiency for residential buildings. To study the feasibility of these storage technologies, different energy systems including on-grid, off-grid and off-grid with 100% renewable are considered. Moreover, different demand scales (single buildings and districts) are used. The results for this research show that neither Li-ion battery and nor pumped hydro are not feasible in on-grid system due to low cost of grid electricity in British Columbia. In both off-grid and off-grid with 100% RES, storage systems (Li-ion and PHES)are installed in most of energy systems as results of high diesel fuel cost and fluctuation of renewable energy sources. In addition, in energy systems with seasonal changes integrated renewable energy PH installation is more feasible comparing with Li-ion.

Finally in chapter four, two remote community are studied using energy hub model. In this research, we use hourly data and then comparing them with hourly average and yearly average data since these profiles are easily calculated using annual demand (which is available in Natural Resource Canada). Moreover, various scenarios for their energy systems are considered which their results shows integration of storage technologies with energy systems significantly reduces equivalent annual cost and carbon emission of the system.

This thesis combine many different aspects of hybrid energy system design with goal of mitigation in carbon emissions and cost reductions. It compares different energy storage technologies and studies their application in energy systems. The results show that each energy system is combination of variables and constraints which highly affect the optimal design of the systems.

5.2 Future work

There are significant potentials for future work with this project. Improving energy systems by designing all details components of energy converters and energy storage systems would be very interesting. In this case, adding PV panels area constraints based on roof area could be an option. Moreover, pumped hydro design can be in more details including the height constrains and reservoir volumes.

It would also be interesting to include other energy demand including heating demand and hot water to system which bring the option to include more converters and other types og storage technologies. Additionally, developing approximate demand data would be an option which can be very helpful in future design specifically in lack data these days.

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