Energy Storage System Sizing Optimization for Remote Isolated Power Systems For Integrating Renewable Energy Systems

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Abstract

Coupling energy storage systems with renewable generation systems has a variety of advantages including: increasing the penetration of renewables, reducing curtailment, providing energy security, lowering greenhouse gas emissions and providing an array of ancillary services. These advantages are multiplied for hybrid off-grid power systems. However, sizing both the energy storage system for both energy capacity and the power rating can be difficult in these remote locations, as modularity, solution characteristics, transportation and installation logistics must be taken into consideration. This analysis simulates one year of energy generation and load based on real data from the remote community of Old Crow Yukon Territory, Canada. Throughout the year data pertaining to the effect of the energy storage system on the remote power system are collected. This information is used to find the optimal energy capacity and power rating for the remote isolated power system, using a specific energy storage dispatch logic. Seven parameters are used to find the optimal solution: cost of energy, cost of power, cost of fuel, cost of curtailment, cost of reserve, cost of insufficient power, and cost of blackouts. Each parameter is compared on the basis of levelized cost of energy and a specific weighting factor. Three cases are examined for different weighing factors, to demonstrate the flexibility of the approach to serve specific purposes. Case 1 examines equal values across all weighting factors. Case 2 focuses on fuel consumption and curtailment and Case 3 focuses on energy security and reliability.

Keywords

Optimization, Simulation, System Reliability, System Adequacy, Remote Power Systems, Hybrid Power Systems

1 Introduction

There are 86 remote communities within Canada's northern territories, many of which rely completely on fossil fuel based electrical power generation. Difficulties in transporting fuel and a growing interest to become less dependent on fossil fuels is driving a shift towards renewable resources such as wind and solar energy. High penetrations of these renewable resources can lead to technical challenges with regards to power system adequacy, security, and stability.

These technical challenges can be addressed through means of curtailing the renewable resource. However, this increases the levelized cost of energy while decreasing the capacity factor of the renewable resource. Another method of addressing and mitigating these challenges is through the implementation of an Energy Storage System (ESS). The ESS can reduce curtailment as well as deliver or consume energy during connection or loss of the resource. The implementation of an ESS can provide some of its own challenges. The energy capacity and power rating are dependent on the requirements of the grid and the dispatch logic used to control the ESS.

This study proposes a method of optimization that selects the most appropriate energy capacity and power rating for the ESS according to the specific isolated grid and ESS dispatch logic. The optimization method proposed within this analysis examines many factors pertinent to isolated power systems: cost of energy, cost of power, fuel saved, renewable resource curtailment, cost of reserve capacity, the cost of inducing a blackout from an insufficient power rating, and saved cost from avoiding a black out. These seven parameters are compared through the levelized cost of energy.

The optimization method is demonstrated through its application on the isolated power system of Old Crow, Canada for the initial testing system within a MATLAB based simulation tool. The remote community of Old Crow has a population of approximately 250 people, the majority of whom are citizens of the Vuntut Gwitchin First Nation (VGFN) [1]. The VGFN are intent on implementing a project to introduce a solar photovoltaic plant and an ESS to reduce the amount of diesel energy used in the community. The community is located north of the arctic circle, and therefore experiences long days and high amounts of reflected sunlight in the shoulder seasons to be used for photovoltaic generation. The optimization method proposed in this paper will provide an appropriate size for an ESS to meet the needs of VGFN and ATCO Electric Yukon (the local utility) for the Old Crow Solar Project, expected to be deployed in 2019.

The Old Crow electrical power system, shown in Figure 1, is an ungrounded delta radially configured system. Five diesel electric generators provide power directly to the system at a primary system voltage of 2.4 kV line-to-line. The community has a peak winter load of approximately 550 kW and a low summer time load of approximately 120 kW.

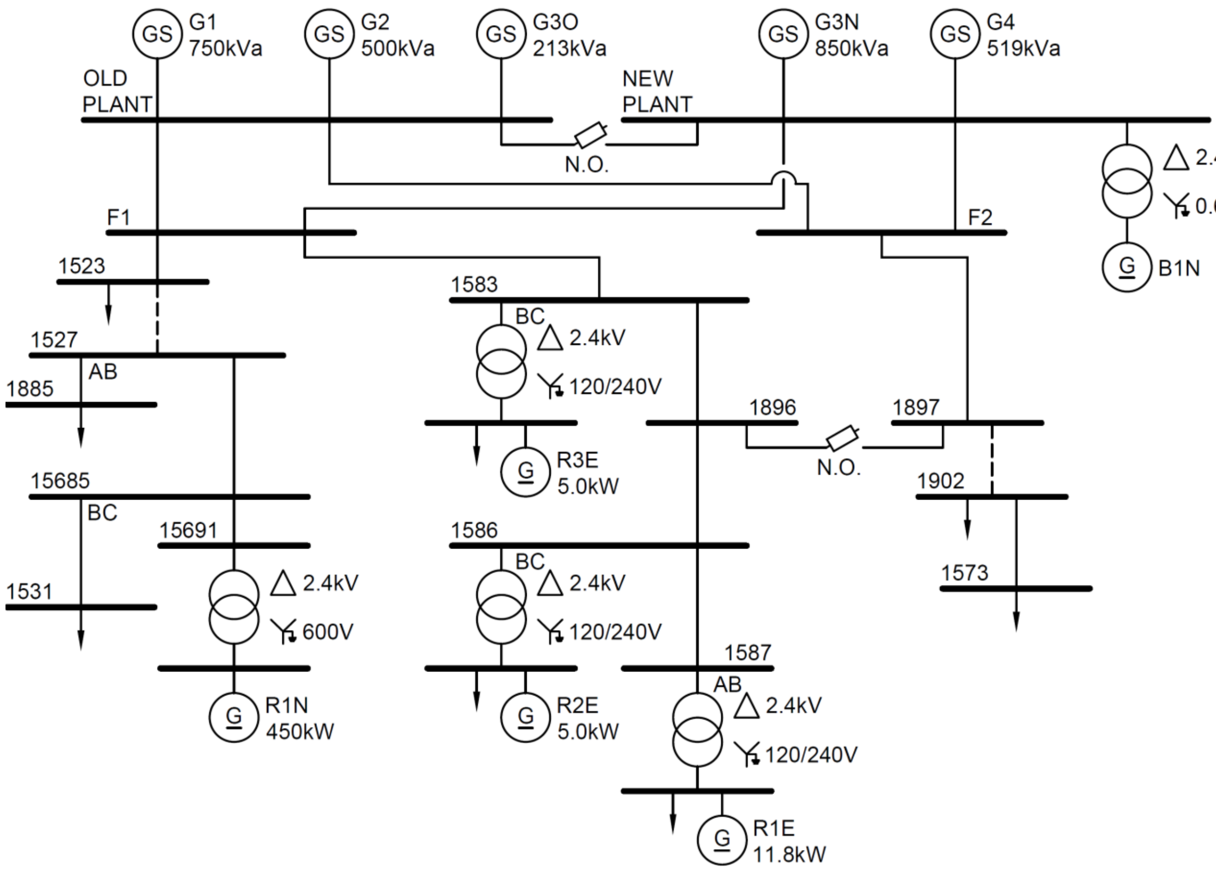

Figure 1: Single line diagram of Old Crow Yukon isolated electrical grid

The single line diagram also shows the point of interconnection of the proposed solar plant, R1N, and ESS, B1N.

2 Modelling

The optimization framework is employed on a MATLAB model of the Old Crow electric system, which comprises: dynamic loads and sources, protection devices, electrical storage and transmission lines. The MATLAB models were developed from parameters and datasets obtained from ATCO Electric Yukon's CYME model and system profiles, OEM parameters and datasheets, and standard electric power system models where real data is unavailable.

Before a renewable resource is connected to a system a grid impact study is performed to quantify the influence the renewable generation plant will have on the system as well as any technical issues that may arise from the interconnection. A method of addressing the generation plant's effect on the system is through quasi-static time series analysis [2]. Quasi-static time series analysis performs sequential steady-state power flow calculations at each time step. This method provides multiple advantages particularly the ability to examine daily or seasonal interactions between the load sources of generation [3].

The use of the phasor method in the simulation domain not only allows for the power flow of the system to be analyzed through quasi-static time series analysis, but it also allows for the option of examining electrical properties of the system such as: over- and under-voltages, line thermal limits (i.e. current limits), voltage profiles and transmission line losses[3][4]. While other analyses must be performed for a complete grid impact study assessment, this style of simulation allows the examination of the system's behavior over the course of a day to that of a year.

The load data are provided by the utility, ATCO Electric Yukon, in 10 minute time steps over the course of a year. This data is multiplied by 1.1 to represent the expected load growth for Old Crow in 2020. More data points are added through linear interpolation between data points to reach a resolution of one minute. A one minute resolution meets the requirements to achieve minimal error [3].

The isolated grid uses dynamic load models to consume active and reactive power. The load models import the power data received from ATCO Electric Yukon, which contains the total power consumption of the community over the course of a year in a one minute resolution. The loads are distributed proportionately throughout the system according to the distribution transformer ratings, which were obtained through the existing model data. The combined total of all the loads sums to the system load demand provided by ATCO.

The dynamic load block, Figure 2, takes the proportional power profile and the power factor angle provided by the utility provider, ($\theta = 0.132$ rad), to create both active and reactive power. The active and reactive power are multiplied by the voltage to the power of constants *np* and *nq* [5]. These are constants that can be set to represent constant power, constant current or constant inductance by using the values of 0, 1 or 2 respectively For the purpose of this study, where the active and reactive demand of the system is known *np* and *nq* are set to 0 to consume constant active and reactive power according to the system demand. The power is multiplied by negative one to indicate consumption before being divided by the voltage at the terminals creating a negative current acting as a power sink.

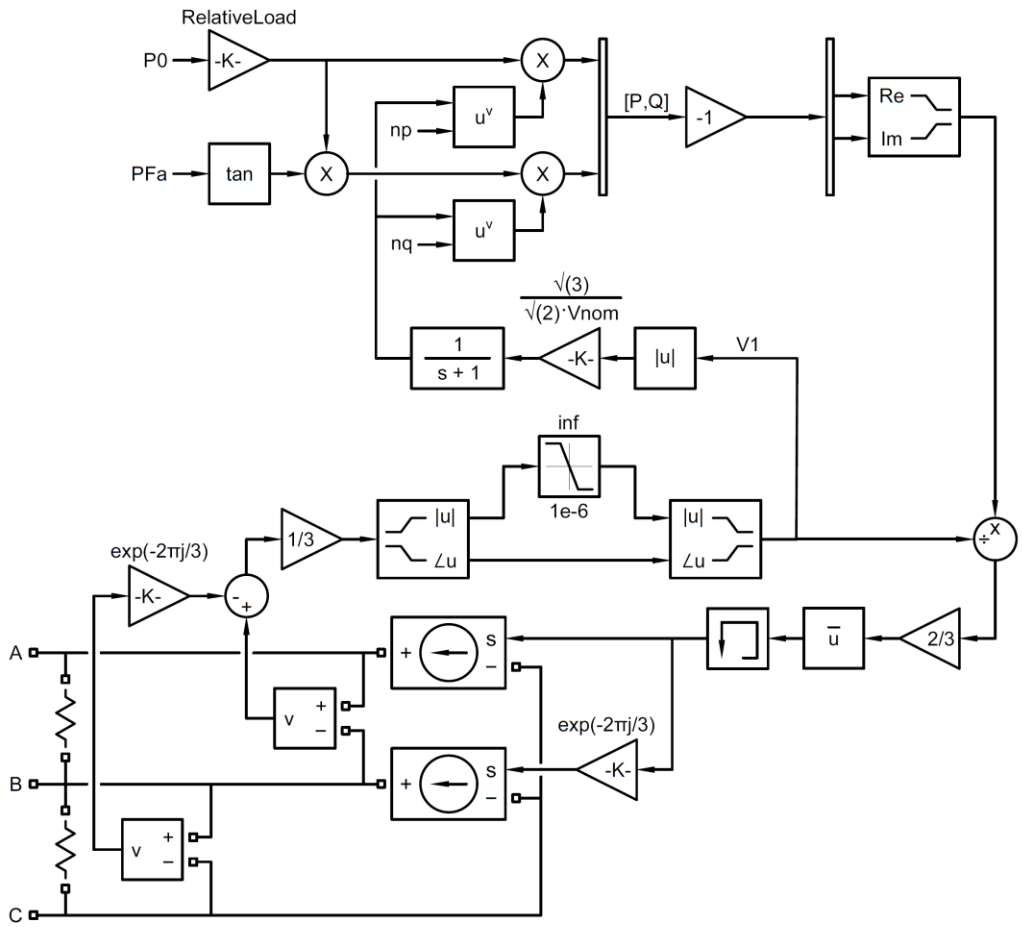

Figure 2: Dynamic load model used to represent loads on the isolated grid

The renewable energy generation plant uses a dynamic model to represent a power source within the system. This model is similar to the dynamic load model, however, in this case power is produced as opposed to consumed, and therefore the gain of negative one is removed. Similar to the dynamic load block the renewable power plant is provided data containing the expected power production of a dual east-west facing 450 kW photovoltaic array on a one minute time step throughout the entirety of one year provided by the Vuntut Gwich'in Government, Figure 3. The renewable generation plant operates with a power factor angle of -0.318 (a leading power factor of 0.9; i.e. consuming reactive power) to reduce the potential of a voltage rise between the generation plant and the point of common coupling. Furthermore, the constants of *np* and *nq* are both set to 0 representing constant active and reactive power. The power electronic interface is not modelled for these studies as a transient effects and harmonics are not apparent on the one minute simulation resolution.

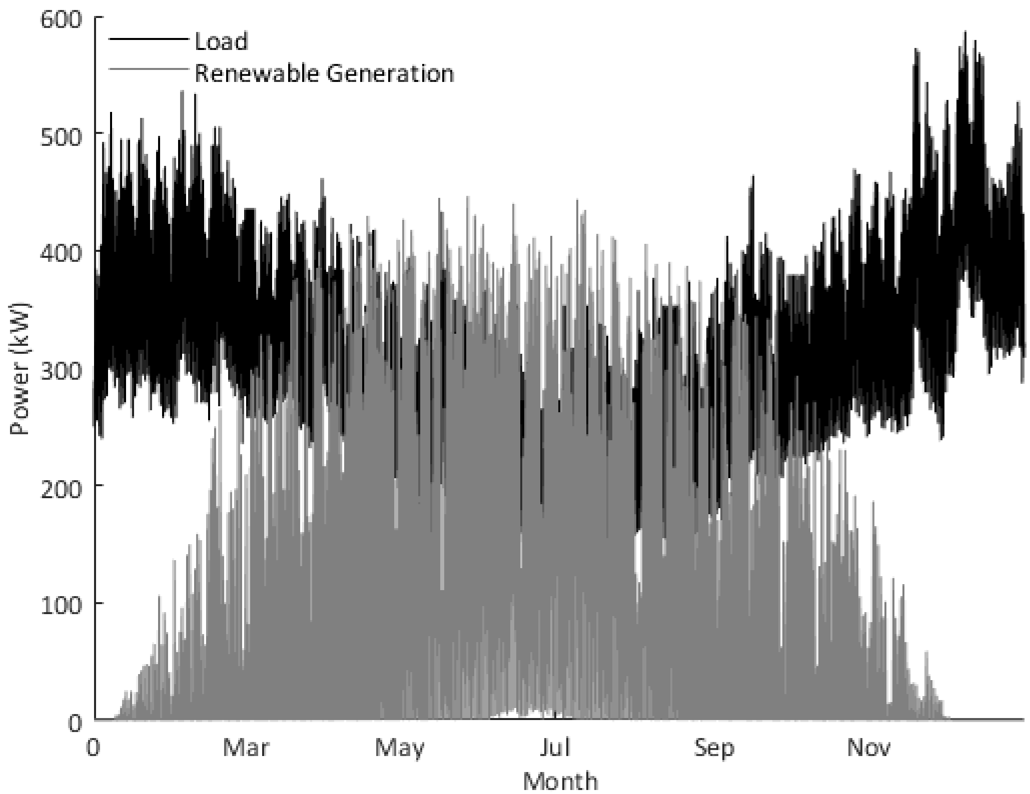

Figure 3: Energy demand of Old Crow and the predicted solar generation profile over one year.

One of the drawbacks of modelling both the dynamic load, renewable generation plant and ESS in this manner is that it requires a memory delay between measuring the voltage, and injecting the current. While this has no drawbacks with respect to the dynamic load block, however, it can result in errors with the renewable plant and the ESS. Where gradients in load exist the renewable plant and ESS are one time step behind in providing this power. This results in minor positive or negative imbalance in the system. The system model avoids the imbalance by generating or consuming this energy with a three phase voltage source representing the fossil fuel based generation plant. This error is quantified to less than 5% of the total renewable energy produced, and thus the results obtained are therefore considered acceptable.

The ESS modelled using a dynamic source block, while the dispatch logic is represented in MATLAB Stateflow. The Stateflow model consists of three states that depict the behavior of the ESS based on an array of parameters. State 1 is considered the idle state. The ESS is neither charging or discharging within this state; however, if the power from renewable resource is non-zero, the renewable resource can input that power into the grid. The generation plant output is maintained above 10% of its minimum loading limit through the curtailment of the renewable resource, if required. If the ESS is below the user set maximum state of charge (SOC), set to 90%, and no renewable power generation then the ESS will remain in State 1.

Should the ESS' drop below the user set maximum SOC and renewable power is being generated, the ESS will transition to State 2, which is generally described as the charging state. Within State 2 the ESS will increase its stored energy by consuming power equal to the output of the renewable energy generation plant while the generator meets the demands of the grid. The ESS will remain within State 2 until the energy capacity has reached the user defined maximum SOC or the renewable energy generation plant is longer producing power. When either of these conditions becomes true the ESS will transition back into State 1 where the logic will determine if further charging is required.

If the SOC of the ESS is greater than or equal to the user defined maximum SOC the ESS will attempt to enter State 3. However, additional conditions must be met before State 3 can be entered:

- The ESS must have been outside State 3 for more than 60 minutes
- If the demand of the grid is no greater than 80% of the maximum power rating of the ESS

If these conditions are not met the ESS remains in State 1. The utility provider has required that the ESS remain outside of State 3 for a minimum of 60 minutes to prevent the diesel generator plant from excessive on off cycling.

While in State 3 the ESS can discharge its stored energy to meet the demand of the grid in isochronous control mode, allowing the generator to be shut down. In the case that the renewable energy plant produces enough power to meet the demand of the grid, the ESS can increase its stored energy to a maximum of 100% SOC; after which the excess renewable power generated is curtailed. When the renewable generation becomes less than the demand of the grid, the ESS makes up the difference. If the power demand of the ESS exceeds 90% of the ESS's rated power, the ESS must remain providing power for two minutes before returning to State 1. Two minutes is representative of the time required to bring an inactive generator online, by ATCO Electric Yukon's standard operating procedures. If the load exceeds the ESS rated power output an "insufficient power" flag is raised and saved for the optimization process.

Connecting the system sources, sinks and storage together are transmission line models. The transmission lines are modeled using a PI equivalent model. The transmission line lengths in isolated communities are typically short (e.g. < 50 km), and therefore the shunt capacitance of the line is ignored. Neglecting the shunt capacitance simplifies the PI equivalent model to a series impedance, which is modeled as a series resistance and inductance. While the transmission lines are short, they cause both losses and voltage drops. In the case of the Old Crow electric power system, the voltage drops can be relatively large with respect to normal operating tolerances. The transmission line resistances and inductances are calculated from the line length and type obtained from the system data provided by ATCO Electric Yukon.

3 Methodology

The optimization examines an array of ESS capacities and rated power outputs. These parameters can vary between 200 to 1200 kWh, in increments of 100 kWh and 200 to 700 kW in increments of 50 kW, respectively. The sample space produces a total of 121 simulations from which the data are collected.

The levelized cost of energy is examined across seven parameters: the cost of energy, the cost of power, the cost of fuel, the cost of curtailment, the cost of reserve, the cost of insufficient power events, and the cost of a blackout. The costs are evaluated as levelized costs of energy, and are weighted to find the total levelized cost of energy. The total levelized cost of energy is displayed graphically as a contour plot with power rating and energy capacity on the X and Y axes respectively.

To find the optimal energy capacity and power rating the MATLAB function *min* is used to find the lowest total levelized cost of energy. This is performed for three cases that apply weighting factors that focus on different areas of interest for the utility and community: equally weighted, a focus on fuel consumption and curtailment, and a focus on energy security and reliability. The three cases demonstrate the applicability and differences of the optimal result of both energy capacity and power rating for each specific purpose.

3.1 Capital Cost of Energy

The total life cycle cost, used to find the levelized cost of energy, represents all the money spent within the life span of the ESS. This includes the initial capital cost, any operation maintenance costs, refurbishment if necessary, and any applicable salvage or disposal costs. For the purpose of this study, the operations and maintenance is assumed to be zero as it is difficult to estimate for a remote northern community and is assumed to be incorporated in the operation and maintenance cost of the existing generation facility. Typical end of life of a lithium ion battery is when the energy capacity reaches 70% of the original capacity due to cycling. This is estimated to be approximately 10,000 cycles [6]. After reaching this point the ESS may still be operable; however, the salvage costs are assumed to be zero in this analysis, due to the difficulties in removing infrastructure of this scale from remote communities. It is likely that any installed infrastructure will remain on the system until it is no longer safe to operate. At which point it will remain in situ, but not in operation.

The number of cycles that the ESS experiences in a year is collected from the simulations. This is extrapolated to find the total number of cycles the system is likely to experience in 25 years, which is the estimated expected life of the project. Should the expected number of cycles be greater than 10,000 a refurbishment cost is applied to the total life cycle cost.

The capital cost of energy is found by multiplying the cost of energy 600 $/kWh, C_E, by the rated energy capacity, E_{rated} [7][8]. The total life cycle cost of energy capacity, $TLCC_E$¸ is found by adding the capital cost with that of any applicable refurbishment costs. Refurbishment of the technology is assumed to be the capital cost plus the expected rate of inflation, *inf = 1.7%* [9], after the specified number of years, *j*, at which the refurbishment occurs. Therefore, the $TLCC_E$ can be found through Equation (1).

$$TLCC_E = C_E E_{rated} \sum_{j=1}^{N} \left(\left[1 + \left(1 + \frac{inf}{100} \right)^j \right] \left(\frac{1}{(1+d)^j} \right) \right) \quad \textbf{(1)}$$

If refurbishment is not required the total life cycle cost of energy is calculated as the capital cost of the ESS. The discount rate, d, is set to 5.25%, which is the rate used by Yukon Energy Corporation [10]. Equation (1) is given as a summation as it would typically include operations and maintenance.

The levelized cost of energy of the ESS is found with respect to the total energy stored and discharged from the ESS. It is calculated through the total life cycle cost and the uniform cost recovery factor shown in Equation (2) [11],

$$LCOE_E = \frac{TLCC_E * UCRF}{Q} \quad \textbf{(2)}$$

The uniform cost recovery factor, *UCRF*, is the ratio of a constant annuity to the present value of receiving that annuity. Defined as,

$$UCRF = \frac{d(1-d)^N}{(1+d)^N - 1} \quad \textbf{(3)}$$

Where, *N=25,* is the length of time the levelized cost of energy is analyzed over. In the case of this analysis *N* is set to 25 years. The uniform cost recovery factor is independent of the levelized cost and has the same value for all levelized costs examined within this analysis.

3.2 Capital Cost of Power

The capital cost of power uses the cost per kW and the rated power capacity to create the capital cost of power, C_P, set to 1200 $/kW, for each examined power capacity [7][8]. Similar to, the total life cycle cost of energy, each power capacity is examined over 25 years and a refurbishment cost is applied if the estimated life cycle is less than this time span. Furthermore, no salvage value is applied to the ESS for this study, and the operation and maintenance of the system is considered to be zero.

$$TLCC_P = \left(C_P + C_P\left(1 + \frac{inf}{100}\right)^j\right)\left(\frac{1}{(1+d)^j}\right) \quad \textbf{(4)}$$

The total life cycle cost of power, $TLCC_P$ is used to calculate the levelized cost of energy for power, $LCOE_P$, Equation (5).

$$LCOE_P = \frac{TLCC_P * UCRF}{Q} \quad \textbf{(5)}$$

3.3 Cost of Fuel

The simulations record the power output from the generator plant for every time step. The generator plant dispatch logic and the diesel generator heat rate curves are applied to the power to calculate the total amount of fuel consumed in litres, *L*. With the intention of reducing the levelized cost of energy there is incentive to reduce the amount of fuel used. This not only saves money through the purchasing of the fuel but also any applicable carbon taxes. The carbon tax used in this analysis is 50 $/tonne, as set forth by the Canadian federal government [12]. However, alternate carbon pricing schemes can be used such as, the suggested social cost of carbon (11-212 $/tonne) [13], or cap and trade systems (18-72 $/tonne) [14].

The cost of fuel throughout Canada's northern communities can vary greatly. The cost is dependent on many factors and is specific to every site. A remote community accessible by road may pay 0.19 $/kWh for the fuel alone, whereas a fly-in community may have a cost of fuel that exceeds 0.50 $/kWh. The variation in price will influence the optimal ESS solution. This analysis uses the cost of fuel for Old Crow Yukon, 0.54 $/kWh [15], and the approximate plant efficiency provided by ATCO Electric, 3.3 kWh/L, to find the cost of fuel at 1.91 $/L.

The total life cycle cost of fuel, $TLCC_F$, is found through the examined period of time with the cost of fuel, C_F, increasing with the rate of inflation and the carbon tax, T_C. As the tax is provided in dollars per tonne the increase in fuel cost for the carbon tax is found through multiplying of litres consumed by the generator plant, L, by the heat rate of diesel fuel, H_R = 0.0382 GJ/L [16], to find the number of gigajoules of energy produced by the generators. The energy is converted into tonnes of carbon dioxide through the multiplication of the emissions factor, ϵ_m 0.0741 tonne/GJ [17].

$$TLCC_F = \sum_{j=1}^{N}\left(\left[L\,C_F\left(1+\frac{inf}{100}\right)^j + L\,\epsilon_m H_R\,T_C\right]\left(\frac{1}{(1+d)^j}\right)\right) \quad \textbf{(6)}$$

The rate of inflation is not applied to the carbon tax as it is expected to cap at 50 $/tonne in Canada by the year 2022, with no future plans to increase over time.

The total life cycle cost is used to find the levelized cost of energy for each of the 121 energy capacities and power ratings examined. Unlike previous levelized cost of energy calculations, the annual diesel energy, Q_d, is used here as this particular calculation is focused on the levelized cost of energy of the diesel plant as opposed to ESS, shown in Equation (7),

$$LCOE_F = \frac{TLCC_F * UCRF}{Q_d} \quad \textbf{(7)}$$

3.4 Cost of Curtailment

The curtailment of energy from a renewable resource reduces the total energy output, and therefore increases the levelized cost of energy. The ESS, with the specific dispatch logic applied in this analysis, allows for the grid to host a higher penetration of renewable energy, while reducing the total amount of curtailment required to maintain power balance [18].

Reducing the amount of curtailment required is a benefit to the renewable resource plant, and also decreases levelized cost of the ESS. Minimizing the amount of curtailed energy allows the utility to provide as much renewable resource as possible to the isolated community while maintaining system adequacy.

The amount of curtailed energy, Q_C, varies with regards to the energy capacity and power rating of the ESS used on the grid. The total life cycle cost of curtailment, $TLCC_C$, is found through multiplying the total energy curtailed by the price rate of energy, C_R, set to 0.74 $/kWh for Old Crow Yukon [13], and the expected rate of inflation, Equation (8).

$$TLCC_C = \sum_{j=1}^{N}\left(Q_c C_R\left(1+\frac{inf}{100}\right)^j\left(\frac{1}{(1+d)^j}\right)\right) \quad \textbf{(8)}$$

The levelized cost of curtailment is examined using a separate method to those used above. The amount of energy curtailed is smaller than the total annual energy produced by the renewable energy plant. Therefore, to prevent the artificial inflation of the levelized cost of energy, a slightly different approach to is used. The levelized cost of energy is examined as an increase in cost due to the curtailment, expressed as Equation (9), where Q_S is the total renewable energy.

$$LCOE_C = \frac{TLCC_C * UCRF}{Q_S + Q_C} - \frac{TLCC_C * UCRF}{Q_S} \quad \textbf{(9)}$$

The sum of the curtailed energy, and the renewable energy input to the grid represents the total possible renewable energy generation. The levelized cost of the curtailed energy is found relative to the theoretical energy production. This is then subtracted by the levelized cost relative to the actual energy produced. This method not only prevents the artificial inflation of the levelized cost but also captures the amount of curtailed energy. Equation (9) can be simplified to produce Equation (10).

$$LCOE_C = UCRF * TLCC_C \left(\frac{Q_C}{Q_S\,(Q_S + Q_C)}\right) \tag{10}$$

3.5 Cost of Reserve

Lithium ion battery manufacturers state that the life cycle of a battery can be increased by reducing the depth of each discharge cycle. By reducing the depth of discharge by 20% the number of cycles before reaching the estimated end of life can be increased to approximately 10,000 [6]. Furthermore, lithium ion batteries experience an exponential decrease in voltage at low SOC, and an exponential increase in voltage at high SOC [19]. Therefore, the dispatch logic operates the ESS nominally between 10% and 90% SOC. This increases the lifespan of that battery as well as avoids the regions of exponential dc-voltage growth and decay. It should be noted that an ESS will continue to function at the proposed end of life; however, it is expected to operate at 70% of its original energy capacity [6].

The cost of reserve is derived from the amount of energy above the chosen 10% that is required to provide 5 minutes of spinning reserve and emergency backup for the isolated system. The energy capacity of this emergency backup power is assumed to be the ESS's maximum power rating for 5 minutes. The time required to start and synchronize a diesel generator on the Old Crow grid is approximately 2 minutes. Providing 5 minutes of reserve energy allows for the generators to begin producing, with a factor of safety.

The total life cycle cost of reserve, $TLCC_R$, is calculated from the cost of energy, C_E, used in the capital cost of energy section above, and the amount of energy above 10% capacity, Equation (11). If the total life cycle cost of reserve is negative, it is assumed to be zero.

$$TLCC_R = C_E\left(P_{rated}\frac{5}{60} - 0.1E_{rated}\right) \tag{11}$$

In a scenario where emergency backup power is required (e.g. the diesel generation plant powers down) the ESS can dip below the 10% capacity rating, which is considered a hard limit during normal operation. The emergency energy reserve of the ESS is present to provide time for a second generator to be brought online. Should the issue still exist after the allotted time of 5 minutes a blackout has occurred and maintenance is likely required. Therefore, no advantage is provided to batteries where 10% of the capacity is greater than 5 minutes at maximum rated power.

The levelized cost of energy of reserve, $LCOE_R$, is calculated with Equation (12). The total life cycle cost will be smaller than the capital costs, and with therefore have less influence over the resulting total levelized cost of energy.

$$LCOE_R = \frac{TLCC_R * UCRF}{Q} \tag{12}$$

A higher minimum operating SOC (i.e. greater than 10%) will not only increase the cost of reserve, but it will also influence the ESS energy input into the grid.

3.6 Cost of Insufficient Power

The rated power capacity of the ESS may not be sufficient to meet the demands of the grid. To avoid blackouts, a condition is added to the ESS dispatch logic to transfer voltage and frequency control back to the generation plant when the demand reaches 90% of the rated power capacity. However, the synchronous generators require approximately 2 minutes to start, synchronize, and provide power to the grid. Therefore, the ESS must continue to provide power for that period of time. Should the demand exceed the rated power capacity of the battery a flag is output from the simulation.

Each of these flags represents a point in time when the ESS is incapable of maintaining power balance and a blackout would occur. Current operating procedure in Old Crow is to black start the grid with the synchronous generator plant, thus limiting the blackout to a short-term event.

Blackouts have an inherent cost associated with them. The cost of a black out is not only that of lost revenues through non-delivered energy but also any potential monetary costs, such as any required maintenance but also the cost of lost reputation as a reliable energy distributer. Sullivan et al. [20] provides the estimated cost of non-delivered energy for residential demand during blackouts of varying lengths: momentary, 30 minutes, 1 hour, 4 hours and 8 hours. As the blackout would have a short duration, the cost of non-delivered energy, C_{NDE}, for a momentary blackout is used. Set at \$21.60/kWh for residential power consumption. This value may not be accurate for small isolated communities as it is difficult to quantify. However, it is used here to demonstrate the functionality of the optimization tool.

To find the total life cycle cost of insufficient power, $TLCC_I$, the number of insufficient power flags, F_{in}, is multiplied by the total cost of non-delivered energy with the expected rate of inflation for every year throughout the analysis and the discount rate, providing Equation (13),

$$TLCC_I = \sum_{j=1}^{N} \left(F_{in} \left(C_{NDE} P_{rated} \frac{5}{60} \right) \left(1 + \frac{inf}{100} \right)^j \left(\frac{1}{(1+d)^j} \right) \right) \tag{13}$$

The total energy not delivered to the grid for each blackout is the rated power of the ESS, P_{rated}, for a total of 5 minutes. A time span of 5 minutes is used here as it is the same time span as that set to the ESS's reserve energy, including the 2 minutes required to start the synchronous generators and a measure of safety. The levelized cost of energy for insufficient power, $LCOE_I$, is calculated using a similar method to the curtailment, where Q_F is the annual non-delivered energy, to avoid artificial inflation of the levelized cost, as provided in Equation (14).

$$LCOE_I = TLCC_I * UCRF \left(\frac{Q_F}{Q(Q + Q_F)} \right) \tag{14}$$

3.7 Cost of Blackout

Finally, the cost of avoiding a blackout is considered within the optimization of the ESS. With the correct dispatch and control logic is formulated such that the ESS can be capable of picking up the load should a synchronous generator power down unexpectedly. However, should the demand of the grid be larger than the power rating of the ESS the blackout cannot be prevented by the ESS and will occur. The frequency of these blackouts is found with the fraction of the load that is greater than the rated power output of the ESS. The frequency of the generator plant powering down, N_f, is estimated to be five times per annum. Blackouts that occur due to a fault on the system cannot be prevented by the ESS, and therefore are not considered within this analysis.

The number of blackout events that occur, with the ESS on the grid, N_b, is estimated to be the total number of power down events per annum multiplied by the fraction of the load that is greater than the rated power output, F_p. This is expressed in Equation (15),

$$N_b = N_f F_p \qquad \textbf{(15)}$$

During the blackout the utility inherits the burden of the cost of non-delivered energy. The same rate of $21.60/kWh is used as per the previous section. The non-delivered energy is assumed to be the average load, $\bar{L}$, throughout the year for a time span of 5 minutes. During a blackout none of the available generators are running, and thus no fuel is consumed, and therefore the cost of fuel can be subtracted from the cost of non-delivered energy reducing the cost of a blackout.

The total life cycle cost of blackouts, $TLCC_B$, is found through multiplying the number of blackout events by the cost of non-delivered energy and the saved cost of fuel that is not consumed. The amount of fuel is calculated through the amount of non-delivered energy divided by the assumed heat rate of the generation plant, P_{eff}, which is set to 3.3 kWh/L. This calculated cost is multiplied by an expected rate of inflation providing the final equation,

$$TLCC_B = \sum_{j=1}^{N} \left(N_b \left(C_{NDE} \bar{L} \frac{5}{60} - \frac{C_F \bar{L}}{P_{eff}} \frac{5}{60} \right) \left(1 + \frac{inf}{100} \right)^j \left(\frac{1}{(1+d)^j} \right) \right) \qquad \textbf{(16)}$$

It must be noted that should the cost of fuel be larger than the cost of non-delivered energy the $TLCC_B$ becomes negative. This can lead to the optimization incentivizing blackouts and should be avoided.

The total life cycle cost of blackouts is used to find the levelized cost of energy of blackouts. A similar structure of formula is used to that of the levelized cost of insufficient power. Expressed in Equation (17), where Q_B is the non-delivered energy per annum

$$LCOE_B = TLCC_B * UCRF \left(\frac{Q_B}{Q(Q + Q_B)} \right) \qquad \textbf{(17)}$$

Furthermore, due to the small amounts of non-delivered energy this likely to have little influence over the total levelized cost. However, it would have the effect of dissuading the solution away from smaller power ratings.

3.8 Levelized Cost of Energy Optimization

The optimization processes pairs each levelized cost with a weighting factor that allows for preference to be provided to specific parameters over others. This scalarization approach of approaching the multi-objective optimization facilitates the determination of an appropriate solution among the set of Pareto optimal solutions Similar methods have been used to optimize the dispatch of renewable energy generation systems for a microgrid [21]. For this analysis the sum of the weighting factors set equal to one. The levelized costs and weighting factors are summed to find the total levelized cost of energy according to Equation (18).

$$tLCOE = W_E LCOE_E + W_P LCOE_P + W_F LCOE_F + W_C LCOE_C + W_R LCOE_R + W_I LCOE_I + W_B LCOE_B \quad \textbf{(18)}$$

The minimum of the total levelized cost of energy can be found using MATLAB's *min* function. The *min* function also allows for the location of the minimum value to be found providing the indices required to directly find the energy capacity and power rating that has the lowest total levelized cost of energy.

Three separate sets of weighting factors are applied to produce the three test cases expressed in Table 1. These three test cases allow for the general behavior of the dispatch and optimization to be examined with separate focuses.

Weighting Factors	Energy	Power	Fuel Consumption	Curtailment	Reserve	Insufficient Power	Blackout
	W_E	W_P	W_F	W_C	W_R	W_I	W_B
Case 1	0.143	0.143	0.143	0.143	0.143	0.143	0.143
Case 2	0.02	0.02	0.27	0.27	0.14	0.14	0.14
Case 3	0.02	0.02	0.14	0.14	0.22	0.22	0.22

Table 1: Weighting factors for test cases

The first test case explores equal weighting factors across all examined parameters. This shows the natural solution to the optimization with each parameter having an equal result in the input. The second test case reduces the weighting on the capital costs of both energy and power and focuses on reducing both the fuel consumed by the generation plant and the amount of energy curtailed by the renewable generation plant. Finally, the third case focuses on reducing blackouts and increasing the security of energy, and while reducing the influence of the capital cost on the optimal solution.

4 Results and Discussion

Each levelized cost of energy parameter, as a result of the simulations, is expressed graphically through a contour plot. Each levelized cost contour provides insight into how it alters the total levelized cost, and thus the optimal solution of energy capacity and power rating. These parameters are combine with their weighting factors to produce a total levelized cost of energy from which a minimum or optimal result is found.

4.1 Optimization Components

Examining each of the seven parameters through an energy capacity vs power rating contour plot displays graphically how each parameter will affect the result. The magnitude and variation in values observed in each contour plot provides insight into how each parameter will influence the final result, as well as how a weighting factor may alter these results.

4.1.1 Levelized Cost of Energy Capacity

The levelized cost of energy for the capital cost of energy capacity is shown in the form of a contour plot in Figure 4. As discussed previously the cost of energy is found through analysis of the capital cost and the refurbishment cost. This analysis uses an estimated cost of energy of a lithium ion battery of 600 $/kWh [20][21]. The capital cost is found through multiplying the estimated cost of energy by the energy capacity.

Each contour is labeled with the levelized cost of energy in $/kWh. As expected the levelized cost of energy for the cost of energy increases with increasing capacity. This is most notable with a high energy capacity and a low power rating as shown in Figure 4, where a 1200 kWh ESS with a 200 kW power rating exceeds $0.49/kWh.

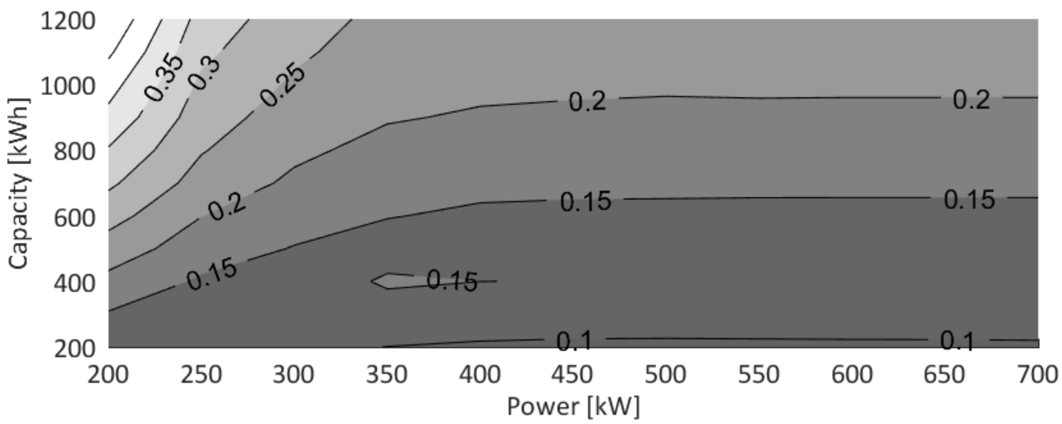

Figure 4: Levelized cost of energy for the capital cost of energy capacity.

There is a local maximum in the levelized cost for ESS with low energy capacity through most of the examined power ratings. This increase is due to the requirement for refurbishment of the ESS. With lower energy capacities the ESS experience a greater amount of cycling and therefore refurbishment is required within the 25 year span of the project increasing the levelized cost.

4.1.2 Levelized Cost of Power Rating

Similar to the previous levelized cost, the levelized cost of energy with regards to the power rating is shown to increase with increasing power, Figure 5. The cost of power is assumed to be 1200 $/kW, the lower end of the price range for a lithium ion battery [7][8]. The capital cost is calculated through the multiplication of the cost of power by the power rating of the ESS. Increasing levelized cost with respect to power rating is an observable trend. This is made more prominent with the refurbishment costs for low energy capacity storage systems due to high cycle induced aging. The need for refurbishment, inflates the price with for low capacity ESS. The combination of these factors pushes the lower levelized costs toward a lower power rating, and higher energy capacity.

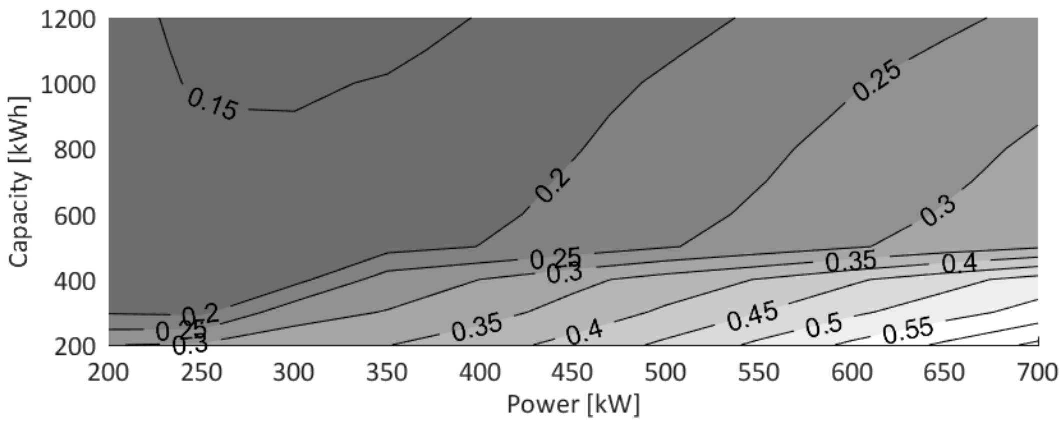

Figure 5: Levelized cost of energy for the capital cost of power rating.

4.1.3 Levelized Cost of Fuel

The contour plot of the levelized cost of energy from the consumption of fuel, Figure 6, shows the behavior of the generator plant with respect to energy capacity and power rating. The figure shows that the energy capacity and power rating of ESS has a direct influence on the levelized cost of fuel. The result shows that ESS with a higher power rating are more favorable.

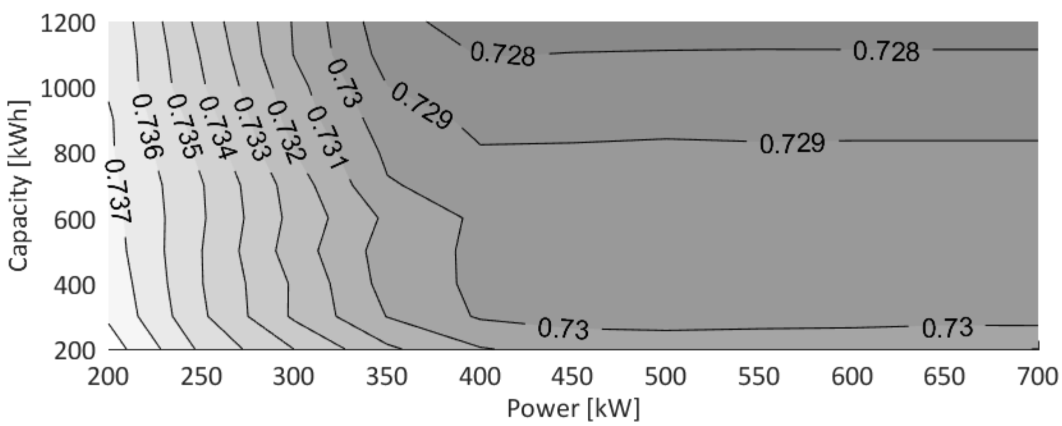

Figure 6: Levelized cost of the fuel consumption of the generator plant.

Figure 6 also shows a steep variation for lower power ratings, evolving into approximately zero gradient areas for higher power ratings. This is likely due to the limitations of the load. The maximum load is measured at approximately 550 kW, while the mean load is approximately 300 kW. An ESS with a higher power rating than the load will not utilize the higher power rating and therefore provides no additional benefit to the system.

The cost of fuel, and therefore the levelized cost of fuel, can vary greatly depending on the location, or time of year. The cost of fuel in this analysis is assumed to be 1.92 $/L, this cost is expected to rise with inflation. The carbon tax is assumed to be held constant at 50 $/tonne as the maximum forecasted cost by the Canadian Federal Government [12].

4.1.4 Levelized Cost of Curtailment

The resulting levelized cost of curtailment is significantly less than the previous explored parameters. Figure 7 shows the levelized cost of curtailment being approximately two orders of magnitude less than the three previous parameters. Lower values of levelized cost of curtailment results in the curtailment having less influence over the total levelized cost of energy.

Figure 7 shows that lower energy capacities and power ratings are more likely to have a higher levelized cost of curtailment. This is due to higher levels of curtailment from the renewable resource in order to maintain energy balance on the system. No examined capacity or rating is capable of completely avoiding curtailment, however the amount of energy curtailed can be reduced by greater than one half within the examined parameters. The percentage of curtailment ranges from approximately 8% of the total renewable energy produced paired with a low capacity and low power ESS, to approximately 3.5% for an ESS with high energy capacity and high power rating.

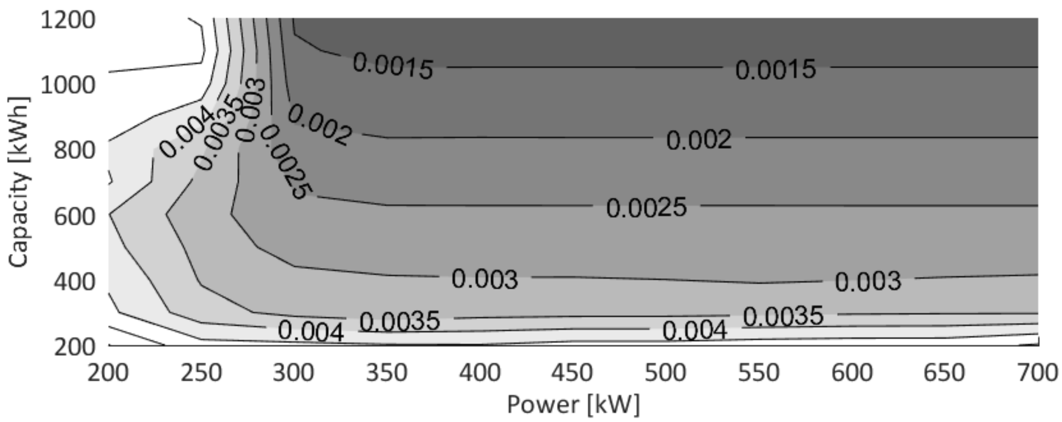

Figure 7: Levelized cost of curtailed energy.

Further observation of Figure 7 shows that the levelized cost of curtailment is mostly influenced by the energy capacity. Increases in levelized cost of curtailment are observed for low power ratings (200 to 250 kW). The increase is also seen to have greater prominence for larger energy capacities. This is likely due to the lower power ratings inability to accept a larger proportion energy from the renewable generation plant, requiring curtailment to meet the minimum loading limits of the synchronous machines.

4.1.5 Levelized Cost of Reserve

Each ESS is operated with an energy reserve to operate at its maximum power rating for 5 minutes, or 10% of the energy capacity, whichever is greater. This limitation reduces the usable energy within the storage system. However, as the ESS is operated above 10% nominally this is considered to have zero cost, while any required storage above 10% SOC is considered within the levelized cost calculation.

For ESS with lower energy capacity and higher power ratings the cost of this reserve is noticeable, as shown in Figure 8. This cost is small relative to the previously explored costs. However, it will dissuade from ESS with a lower energy capacity and a higher power rating from being chosen.

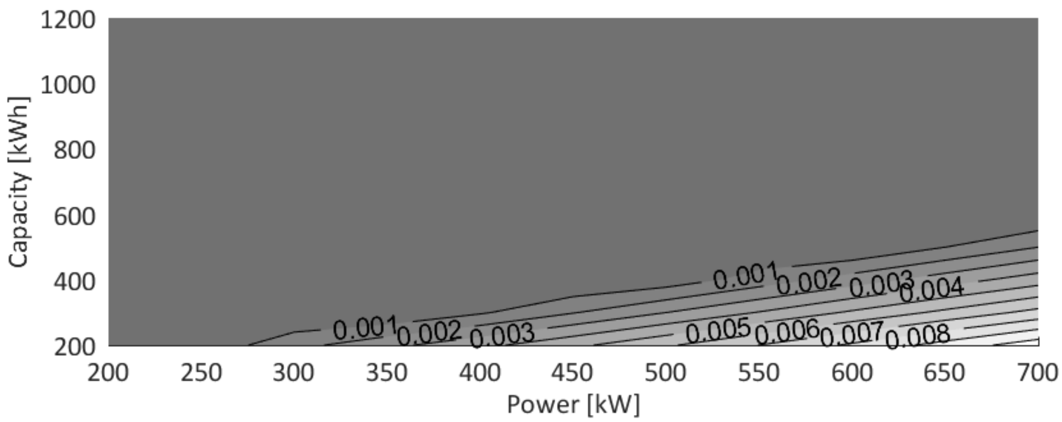

Figure 8: Levelized cost of stored reserve energy.

Ideally no increase in minimum capacity due to reserve would be required, as it is a reduction in the total operational capacity. For example, the 200 kWh ESS with a 700 kW power rating is only capable of utilizing 60% of the total capacity, or an effective capacity of 120 kWh.

4.1.6 Levelized Cost of Insufficient Power

Due to the size of the load many of the power ratings will never reach an insufficient power event. The maximum demand of the load is approximately 550 kW, therefore power ratings above this limit have no opportunity to reach insufficient power, Figure 9 shows a zero levelized cost for these power ratings. Furthermore, the dispatch logic begins the startup of the generation plant when the load reaches 90% the ESS power rating. This provides a buffer to reduce the chances of an insufficient power event.

Power ratings of 350 kW and greater experience no insufficient power events. While the 350 kW power rating experiences only 2 events. These events do not appear in Figure 9 as the levelized cost of the event is four orders of magnitude less than the maximum value. Smaller capacities experience greater than 100 insufficient power events. These are shown to have a far greater influence over the levelized cost of energy.

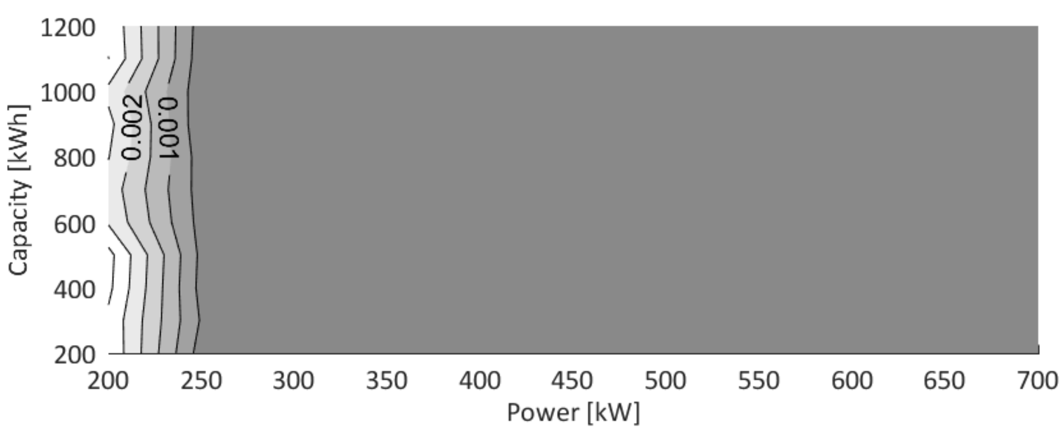

Figure 9: Levelized cost of insufficient power resulting in a blackout.

While the power rating has the greatest influence over the levelized cost, the energy capacity of the storage system has an almost imperceptible effect. However, as larger energy capacities spend more time discharging the possibility of the load exceeding the power rating increases.

4.1.7 Levelized Cost of Blackouts

Unlike the levelized cost of insufficient power, the levelized cost of a blackout, or non-delivered energy, explores the ESS's ability of picking up voltage and frequency control in the case that the generation plant shuts down. The resulting cost of non-delivered energy is due to the inability of the ESS to pick up the demand of the grid. Figure 10 shows that lower power ratings increase the likelihood of an event occurring at a time when the ESS is incapable of picking up the load and therefore resulting in a blackout. Above 550 kW all power ratings are capable of picking up the load, and therefore experience no increase in levelized cost.

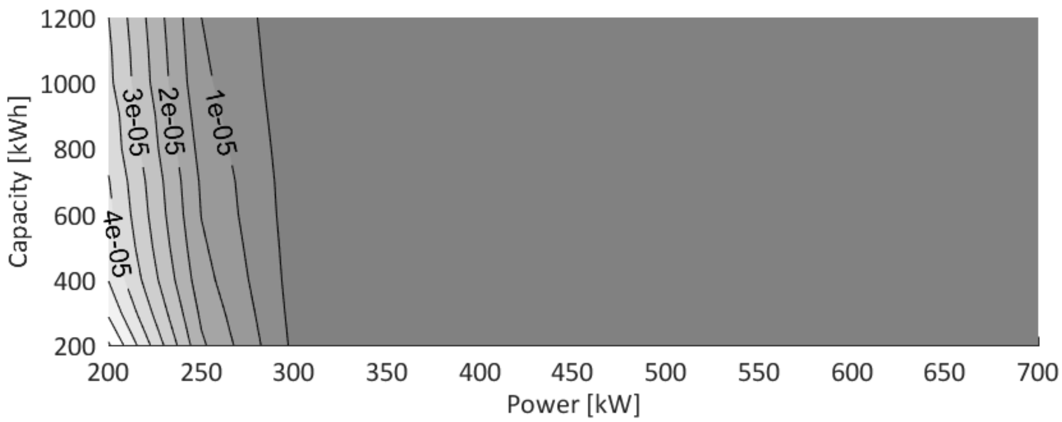

Figure 10: Levelized Cost of non-delivered energy.

The magnitude of the levelized cost of blackouts is due to the assumption that only 5 such events could be prevented each year. The number of plant outages may vary from this assumption; however, outage data is not readily available.

4.2 Case 1

The seven parameters are combined with their respective weighting factors to find the total levelized cost of energy. The minimum of the total is the optimal energy capacity and power rating for the specific microgrid and designated dispatch logic.

Case 1 uses a weighting factor or 1/7 across all seven parameters to find the optimal energy storage solution. Allowing for each parameter to influence the result equally, the results of which are shown in Figure 11. The figure shows some of the behavior observed in the contour plots of the components. Most prominently, ESS with low capacity and high power rating, requiring refurbishment, have a far greater levelized cost. Meanwhile the influence of curtailment can be seen in the regions of low power rating.

The minimum levelized cost of energy, and thus the optimal energy capacity and power rating, is found to be 400 kWh and 300 kW respectively. These locations experience few insufficient power and blackout events throughout the year, while also allowing a high proportion of the renewable energy to be utilized.

The capital cost of energy and the capital cost of power push the results back towards smaller energy capacities and power ratings.

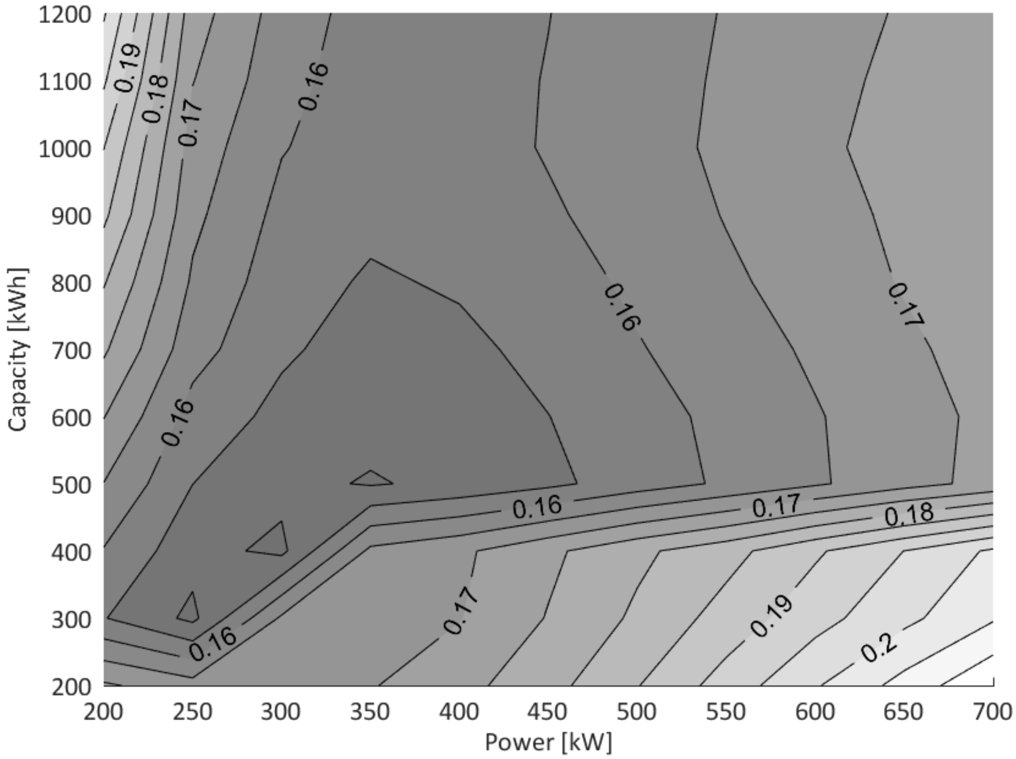

Figure 11: Total levelized cost of energy for all parameters with equal weighing factors.

4.3 Case 2

Case 2 explores the optimal solution with the weighting factors focusing on reducing both fuel consumption and curtailment, while reducing the influence of the capital cost of energy and power. The weighting factors based on the capital cost of energy and power are set to 0.02, while the weighting factors of fuel consumption and curtailment are set to 0.27. As a result, less variation in the levelized cost of energy is observed throughout the contour plot, Figure 12.

The minimum levelized cost for these weighting factors results in an optimal energy capacity and power rating of 500 kWh and 350 kW respectively. Both energy capacity and power rating increase by one step when compared to Case 1. This shows the stability of the solution, and the minimal influence of fuel pricing and curtailment on the capital cost of energy and power rating. However, The low cost of energy with minimal variance stretching from 300 to 500 kW and 500 to 1200 kWh shows that many solutions are near optimal.

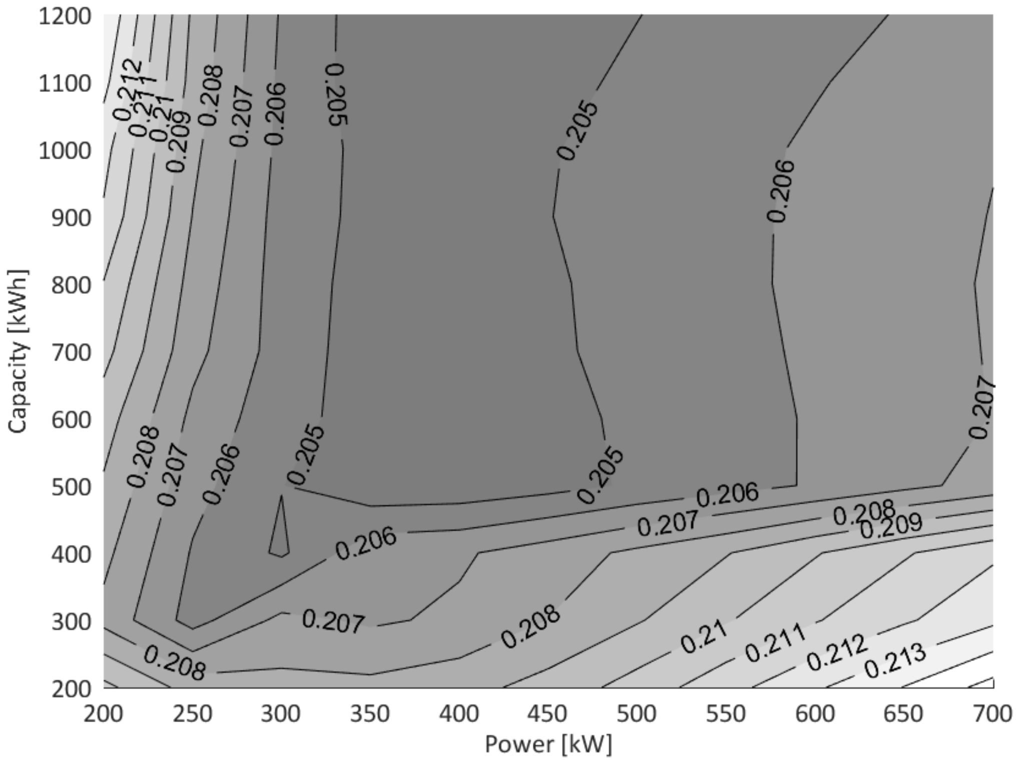

Figure 12: Total levelized cost of energy, weighting factors focused on fuel consumption and curtailment

4.4 Case 3

Case 3 focuses the weighting on avoiding blackouts and insufficient power events, including the cost of reserve. This provides a sizing with the purpose of increasing the security and reliability of energy for the customer. Increasing the weighting factors on the cost of reserve, insufficient power events, and the cost of blackouts. The weighting factors are decreased for the capital cost of energy capacity and power rating.

The resulting values with these weighting factors are shown in Figure 13. The figure has little difference from the previous two cases, with the exception that the values are reduced both in magnitude and variance. Despite decreasing the weighting factors, the influence of the cost of energy capacity and power rating is still seen in the low energy and high capacity range where refurbishment costs are applied. Similar to Case 2 the optimal energy capacity and power rating are 500 kWh and 350 kW respectively providing testament to the consistency of the solution. Further similarities to Case 2 are observed in the low laying centre, with minimal variance indicates that there are many near optimal solutions.

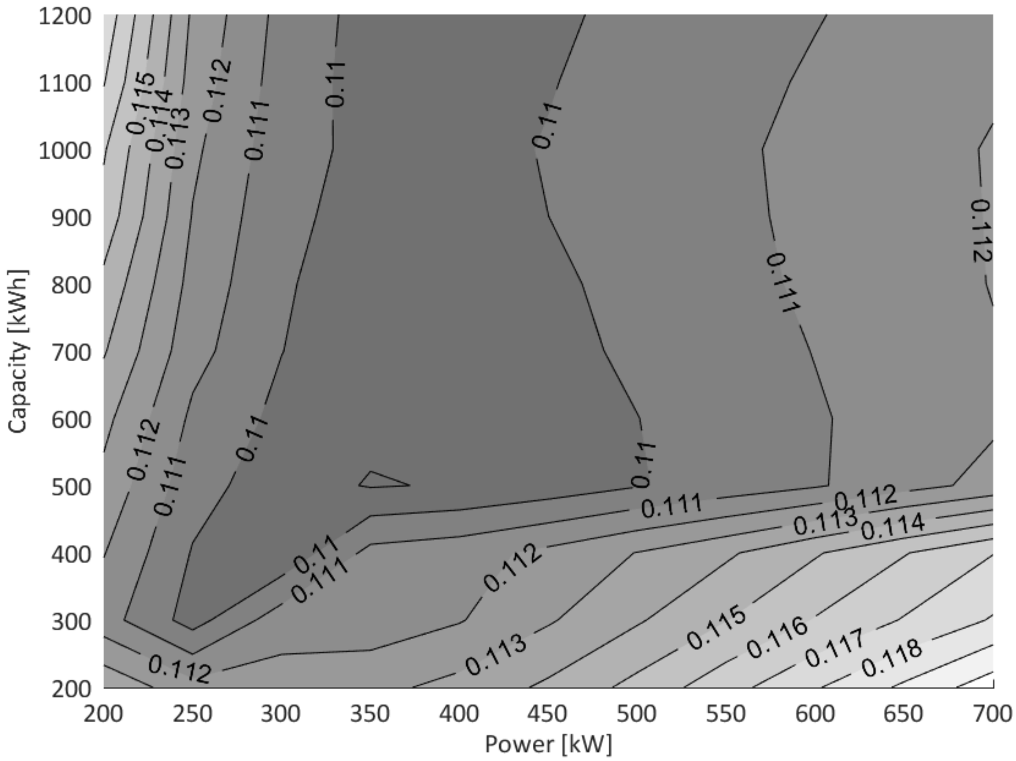

Figure 13: Total levelized cost of energy with weighting factors focusing on avoiding insufficient power and blackout events.

5 Conclusion

Each of the seven parameters examined within the optimization influence the resulting values independently. The flexibility of the optimization too with regards to weighing parameters allows it to be used in a variety of scenarios. Furthermore, the methodology used within this optimization tool is generic and can be applied as a part of any isolated power system study, with any energy storage dispatch and control logic.

Of the seven parameters, the capital cost of energy capacity and the capital cost of power rating shifting the solution to a smaller capacity and power rating, while the cost of fuel does the opposite. The remaining factors are several orders of magnitude less than the previous parameters and therefore have less influence over the solution. However, all these parameters, curtailment, reserve, insufficient power and blackouts, shift the solution to higher power ratings and energy capacities.

With equal weighting factors across all examined parameters the optimal solution is found to be a 300 kW power rating and 400 kWh of energy capacity as shown in Case 1. This combination of capacity and rating has a life cycle such that refurbishment is not required while avoiding the exponential areas of curtailment, fuel consumption, and insufficient power.

Case 2 applies weighting factors to increase the importance of both the consumption of fuel and curtailment of renewable energy. The application of these weights is shown provide an optimal solution that varies slightly with respect to Case 1 in terms of energy capacity, and power rating showing the consistency of the solution. This is expressed further within the results of Case 3.

Case 3 places the focus on energy security and system adequacy through the application of higher weighting values to the cost of reserve, insufficient power and blackouts. The resulting optimal levelized cost is found to be the same as Case 1, which resulted in an ESS sized at, 350 kW and 500 kWh. This shows that the result is consistent at this particular power rating and energy capacity.

The results of this optimization are dependent on the energy storage dispatch logic implemented in the simulations. Changes to the remote power system, or sources of renewable generation may result in alternative optimal solutions. This does however allow for the optimization tool to be used with a variety remote isolated power systems and renewable energy generation types and penetration levels.

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