Techno-economic assessment of using alternative energy technologies at a remote mining operation in the Yukon territory, Canada

Brennan Cicierski

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January 2018

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Abstract
The Canadian mining industry has historically taken efforts to reduce the energy intensity of their operations through energy management and efficiency measures. More recently, due to growing concern over climate change and improving alternative energy technologies, substituting fossil fuel based power systems with lower carbon emitting sources is a promising strategy to cut costs and reduce environmental impacts. This thesis aims to evaluate the techno-economic feasibility of using alternative energy technologies for power generation at a remote mining operation in the Yukon territory of Canada. This is a potential mining operation that is expected to be developed over the next decade, however no mining infrastructure has been constructed. The feasibility of using natural gas, wind and solar energy will be evaluated using site specific renewable energy resource data, mining power demand assumptions, as well as current technology and cost estimations. It was found that diesel generators offer the lowest levelized cost of energy (C$0.295/kWh). However, under a C$50/tonne carbon tax assumption, dual fuel generators capable of mixing natural gas and diesel is the most economic option, offering annual savings of C$600,000 and 6,000 tonnes reduced CO₂ equivalent emissions, compared to diesel generators. Given the case study’s northern latitude and minimal solar radiation, solar energy is not considered to be a competitive alternative to provide electrical power to the mine. A power system consisting of a combination of dual fuel generators, wind turbines (accounting for approximately 10% of the mine’s electricity demand) and lithium-ion batteries has a marginally higher levelized cost of energy than diesel generators under non-carbon tax conditions (C$0.312/kWh). Although wind and solar energy were found not to be economically attractive options in this study, mining operations with access to higher quality renewable energy resources could make meaningful reductions in operating costs and greenhouse gas emissions by implementing hybrid renewable energy systems, including the use of natural gas or dual fuel generators.
Tækni- og verðlægt mat á notkun mismunandi orkugjafa fyrir afskekkta námuvinnslu í Yukon, Kanada

Brennan Cicierski
janúar 2018

Útdráttur
Námuvinnsla í Kanada er sifellt að leita lausna til þess að draga úr orkunotkun sinni með hagýtari og skilvirkarni stjórnun á orkunotkuninni. Hrøð þróun hefur verið á markaði hreinna orkugjafa sökum hnattrænnar hlýnunar og eru þeir orðir samkeppnishaðurír vallkostir í stað jordafniælsnytis þegar lið þar er til lækkanar á kostnaði og minkunnar á neikvæðum umhverfisáhrifum. Markmið þessa verkefnis er að meta framkvæmdarmöguleika þess að skoða aðra vallkosti en jordafniælsnyti til þess að sinna orkuþörðum afskekktra námuvinnslu í Yukon, Kanada. Þessi staður er enn á rannsóknarstígi og enginn innviður hefur verið byggður, en gert er ráð fyrir að hann muni verða nýttur á næsta ártugi. Möguleikar þess að nota náttúrulegt gas, vindorku eða sólarorku verða skoðaðir með því tilliti til endurvinanlegra orku, orkunotkun námuvinnslunnar, aðgengilegri tækní og kostnaði. Disel mótorar voru öðyrasti vallkosturinn hvað varðar levelized cost of energy (C$0.295/kWh). Hinsvegar, ef er gert ráð fyrir kolefnaskattandi undir C$50/tønn, eru tvískiptir rafallar sem geta bleanað saman náttúrulegu gasi og disel besti kosturinn frá efnahagslegu sjóarmiði þar sem notkun þeirra geri sparáð C$600.000 árlega og minnkað útbálástur kolefnis um 6.000 tonn, miðað við venjulega disel rafala. Þar sem viðfangefni þessa verkefnis er á norðilegri breiddargráðu er ekki gert ráð fyrir sólarorku sem samkeppnishæfum vallkosti í rafmagnsframleiðslu fyrir námuvinnslua. Raforkurferi sem samanstendur af tvískiptum rafali, vind túbínum (sem framleiða 10% af orkuþörðum námunnar) og lithium-ion rafhlöðum er með hærri kostnað m.t.t. levelized cost of electricity heldur en disel rafalar ef enginn kolefnisskattur sé tekinn með (C$0.312/kWh). Þó að vind- og sólarorka hafi ekki verið besti efnahagslegi vallkosturinn í þessu verkefní þá getu námuvinnslar með betra aðgengi að endurnýjanlegum orkugjöfum minnkað rekstrarkostnað og úblástur gróðurhúsooftegunda með því að nýta sér tvískipt orkurerfi, þ.a.m. náttúrulegt gas eða tvískipta rafala.
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Jan. 24, 2018
Date

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Preface

This dissertation is original work by the author, Brennan Cicierski.
Contents

Acknowledgements .................................................................................................................................... xv
Preface ......................................................................................................................................................... xvii
Contents ....................................................................................................................................................... xix
List of Figures .................................................................................................................................................. xxi
List of Tables .................................................................................................................................................. xxiii
List of Abbreviations and Acronyms ........................................................................................................ xxiv
List of Symbols .............................................................................................................................................. xxvi
1 Introduction ................................................................................................................................................ 1
  1.1 Motivation ............................................................................................................................................. 2
  1.2 Purpose and Scope ............................................................................................................................... 4
  1.3 Outline of Thesis ................................................................................................................................. 5
2 Background .................................................................................................................................................. 6
3 Literature Review ....................................................................................................................................... 9
  3.1 Mine Power Systems ......................................................................................................................... 9
  3.2 Hybrid Renewable Energy Systems .................................................................................................. 12
  3.3 Techno-Economic Studies ................................................................................................................ 14
4 Methodology .............................................................................................................................................. 17
  4.1 Meteorological Data .......................................................................................................................... 17
    4.1.1 Wind Energy ............................................................................................................................... 19
    4.1.2 Solar Energy ................................................................................................................................ 21
  4.2 System Modeling ................................................................................................................................ 23
    4.2.1 Mine Power Demand ................................................................................................................ 24
    4.2.2 Wind Turbines ............................................................................................................................ 25
    4.2.3 Photovoltaic Solar Panels ......................................................................................................... 27
    4.2.4 Energy Storage .......................................................................................................................... 30
    4.2.5 Fossil Fuel Generators .............................................................................................................. 32
    4.2.6 Summary ....................................................................................................................................... 34
  4.3 Levelized Cost of Energy .................................................................................................................... 35
  4.4 Greenhouse Gas Emissions ................................................................................................................ 36
  4.5 Scenario Evaluation ............................................................................................................................. 37
  4.6 Validation Method ................................................................................................................................ 39
  4.7 Sensitivity Analysis .............................................................................................................................. 39
5 Results ....................................................................................................................................................... 41
  5.1 Scenario Analysis ............................................................................................................................... 41
5.2 Validation ............................................................................................................. 45
5.3 Sensitivity Analysis ........................................................................................... 46
5.4 Carbon Tax ......................................................................................................... 49

6 Discussion ............................................................................................................ 52

6.1 Recommendations ........................................................................................... 53
6.2 Conclusion ......................................................................................................... 56

Bibliography ............................................................................................................. 58

Appendix A Mine-Power Benchmarking .................................................................. 62

Appendix B HOMER User Inputs ............................................................................. 63
List of Figures

Figure 1.1 Map of Canada showing provincial and territorial boundaries (Natural Resources Canada, 2017b) .........................................................................................................................3

Figure 1.2 Electricity generation in Canadian provinces and territories in 2014 (Natural Resources Canada, 2017a) .................................................................................................................4

Figure 2.1 Yukon territory map of main towns and existing road network (Yukon Travel, 2017) ........................................................................................................................................7

Figure 2.2 Average monthly temperature at case study site between 2014 and 2017 (Data for this figure was provided by the Company) ..................................................................................7

Figure 3.1 Typical mill power consumption for different ore types (de la Vergne, 2000, p. 310) ................................................................................................................................................10

Figure 3.2 Electrical power consumption breakdown for Zn-Pb underground mine and mill .................................................................................................................................11

Figure 3.3 Installed diesel power capacity from benchmarking analysis of northern Canadian mines ..........................................................................................................................12

Figure 4.1 Arial view of wind and solar areas near case study site ...............................................18

Figure 4.2 View of targeted area for wind turbine development on top of plateau, looking north-west ........................................................................................................................19

Figure 4.3 Hourly (left) and diurnal (right) wind speed time series data at 70 m above ground level............................................................................................................................20

Figure 4.4 Wind rose for wind speeds at 80 m above ground level (blowing from) .................21

Figure 4.5 View of targeted area for PV solar panel development on top of plateau, looking south .................................................................................................................................22

Figure 4.6 Meteorological weather station operated by previous project owner ....................22

Figure 4.7 Hourly (left) and diurnal (right) solar radiation data collected from weather station ........................................................................................................................................23

Figure 4.8 Power system configuration for all energy technologies connected to mine load ...............................................................................................................................................24

Figure 4.9 Power curve for EWT DW61-1.0 MW wind turbine model (Data for this figure was provided by EWT) ........................................................................................................26

Figure 4.10 Fuel consumption curve for Generac 1,800 kW (prime) diesel generator ........33

Figure 4.11 Flowchart outlining the methodology employed to carry out iterative optimization ...............................................................................................................................38

Figure 5.1 Number of wind turbine optimization for dual fuel/wind scenario ....................43

Figure 5.2 Number of battery unit optimization for dual fuel/wind/battery scenario utilizing seven wind turbines ........................................................................................................44

Figure 5.3 Smoothed power output vs power generated by wind turbines for dual fuel/wind/battery scenario .................................................................................................45
Figure 5.4 HOMER LCOE validation results for energy technologies evaluated in this study ..................................................................................................................................................................................................................46
Figure 5.5 Capital cost sensitivity analysis for dual fuel/wind/battery scenario ..........47
Figure 5.6 Fuel price and wind speed sensitivity analysis for dual fuel/wind/battery scenario .................................................................................................................................................................................................................................................47
Figure 5.7 IRR sensitivity analysis for wind speed and diesel fuel price for dual fuel/wind/battery scenario .................................................................................................................................................................................................................................................48
Figure 5.8 Mine life sensitivity analysis for diesel, dual fuel and dual fuel/wind/battery scenarios .................................................................................................................................................................................................................................................49
Figure 5.9 IRR sensitivity analysis for wind speed and carbon tax price for dual fuel/wind/battery scenario .................................................................................................................................................................................................................................................50
List of Tables

Table 4.1 Technical parameters for EWT DW61-1.0 MW wind turbine (EWT, 2017) ........25
Table 4.2 PV solar panel physical parameters and operating conditions (REC Group, n.d. (b))..................................................................................................................27
Table 4.3 Solar panel operating parameters under STC and NOCT (REC Group, n.d. (b)).27
Table 4.4 Technical operating parameters of Li-ion battery units ..............................30
Table 4.5 Summary of power system components to be used in the scenario analysis ...34
Table 4.6 Summary of economic assumptions for power system components per unit ....35
Table 4.7 GHG emission factors for stationary combustion of fossil fuels (British Columbia Ministry of Environment, 2016) ........................................................................37
Table 5.1 Scenario analysis results: Rated power capacity of energy technologies ....42
Table 5.2 Scenario analysis results: Average power output of energy technologies ....42
Table 5.3 Scenario analysis results: Fuel consumption and economic summary ..........42
Table 5.4 HOMER validation results for annual fuel consumption and wind energy output45
Table 5.5 Scenario analysis results with carbon tax: Fuel consumption and economic summary ..........................................................................................................................50
Table 6.1 Summary of power system options including future work recommendations, with carbon tax ..................................................................................................................................55
Table 6.2 Raw data from mine power benchmarking analysis ......................................62
Table 6.3 HOMER Pro microgrid software user input summary ......................................63
# List of Abbreviations and Acronyms

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>a.s.l.</td>
<td>Above sea level</td>
</tr>
<tr>
<td>Ag</td>
<td>Silver</td>
</tr>
<tr>
<td>°C</td>
<td>Degrees Celsius</td>
</tr>
<tr>
<td>C$</td>
<td>Canadian dollar</td>
</tr>
<tr>
<td>CO₂</td>
<td>Carbon dioxide</td>
</tr>
<tr>
<td>CO₂e</td>
<td>Carbon dioxide equivalent</td>
</tr>
<tr>
<td>Cu</td>
<td>Copper</td>
</tr>
<tr>
<td>DOD</td>
<td>Depth of discharge</td>
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<tr>
<td>GHG</td>
<td>Greenhouse gas</td>
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<tr>
<td>GJ</td>
<td>Gigajoule</td>
</tr>
<tr>
<td>GWh</td>
<td>Gigawatt Hour</td>
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<td>HRES</td>
<td>Hybrid renewable energy systems</td>
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<tr>
<td>IPCC</td>
<td>Intergovernmental Panel on Climate Change</td>
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<tr>
<td>IRR</td>
<td>Internal rate of return</td>
</tr>
<tr>
<td>kg</td>
<td>Kilogram</td>
</tr>
<tr>
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<td>Kilometer</td>
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<td>Kilowatt</td>
</tr>
<tr>
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<td>Kilowatt hour</td>
</tr>
<tr>
<td>L</td>
<td>Liter</td>
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<tr>
<td>LCE</td>
<td>Life cycle emissions</td>
</tr>
<tr>
<td>LCOE</td>
<td>Levelized cost of energy</td>
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<tr>
<td>Li-ion</td>
<td>Lithium-ion</td>
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<tr>
<td>LNG</td>
<td>Liquefied natural gas</td>
</tr>
<tr>
<td>m</td>
<td>Meter</td>
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<tr>
<td>MW</td>
<td>Megawatt</td>
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<td>Nickel</td>
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<tr>
<td>NG</td>
<td>Natural gas</td>
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<tr>
<td>NDC</td>
<td>Nationally determined contribution</td>
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<td>NOCT</td>
<td>Nominal operating cell temperature</td>
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<td>Net present cost</td>
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<td>NPV</td>
<td>Net present value</td>
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<tr>
<td>NT</td>
<td>Northwest Territories</td>
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<tr>
<td>O/P</td>
<td>Open pit</td>
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<td>Photovoltaic</td>
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<td>Quebec</td>
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<td>s</td>
<td>Second</td>
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<td>SOC</td>
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<td>Tonnes per day</td>
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## List of Symbols

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<td>Wind turbine power output</td>
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<td>Wind turbine power curve function</td>
<td>kW</td>
</tr>
<tr>
<td>$Q$</td>
<td>Annual energy output</td>
<td>kWh</td>
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<tr>
<td>$SOC$</td>
<td>Battery state of charge</td>
<td>%</td>
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<tr>
<td>$SOC_{min}$</td>
<td>Minimum battery state of charge</td>
<td>%</td>
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<tr>
<td>$t_l$</td>
<td>Local time</td>
<td>Hour</td>
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<tr>
<td>$t_s$</td>
<td>Solar time</td>
<td>Hour</td>
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<tr>
<td>$T_a$</td>
<td>Ambient air temperature</td>
<td>°C</td>
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<tr>
<td>$T_{a,NOCT}$</td>
<td>Ambient air temperature at NOCT</td>
<td>°C</td>
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<tr>
<td>$T_c$</td>
<td>Cell temperature</td>
<td>°C</td>
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<tr>
<td>$T_{c,NOCT}$</td>
<td>Cell temperature at NOCT</td>
<td>°C</td>
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<tr>
<td>$T_{c,STC}$</td>
<td>Cell temperature at STC</td>
<td>°C</td>
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<tr>
<td>$TC$</td>
<td>Total cost</td>
<td>C$</td>
</tr>
<tr>
<td>$TC_{Alternative}$</td>
<td>Total cost of alternative system</td>
<td>C$</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
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<tr>
<td>$TC_{\text{Base case}}$</td>
<td>Total cost of base case system</td>
<td>C$</td>
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<tr>
<td>$TLCC$</td>
<td>Total life cycle cost</td>
<td>C$</td>
</tr>
<tr>
<td>$v$</td>
<td>Wind speed</td>
<td>m/s</td>
</tr>
<tr>
<td>$v_{ci}$</td>
<td>Cut-in wind speed</td>
<td>m/s</td>
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<tr>
<td>$v_{co}$</td>
<td>Cut-out wind speed</td>
<td>m/s</td>
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<tr>
<td>$v_r$</td>
<td>Rated wind speed</td>
<td>m/s</td>
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<td>$\omega$</td>
<td>Hour angle</td>
<td>°</td>
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Chapter 1

Introduction

The way in which energy is viewed is changing, energy affects our day-to-day lives and is a common indicator of national development. Since advancements of the steam engine in the 1700’s, fossil fuels, namely coal, oil and natural gas (NG) constitute 85% of the world primary energy consumption (BP, 2017). However, consumption of these fuels results in harmful gases released into the atmosphere creating a pseudo greenhouse effect, thereby warming the earth’s climate. According to the Intergovernmental Panel on Climate Change (IPCC) First Assessment Report, if no effort is made to reduce consumption of fossil fuels (business-as-usual scenario), the global mean temperature is expected to rise by about 4°C by 2100 from pre-industrialized levels (Houghton, Jenkins, & Ephraums, 1990). A temperature rise of this magnitude would have serious implications to the earth’s environment, causing more extreme weather events like droughts, floods and hurricanes, sea level rise, and species extinction. Therefore, efforts have been made by the international community to reduce fossil fuel consumption through improved energy efficiency, conservation and substitution with renewable energy.

Greater adoption of renewable energy is a promising method to decarbonize our economy, since these sources can often act as direct substitutes for fossil fuels. Renewable energy sources rely on the earth’s natural processes such as sunlight, wind and geothermal heat, and are naturally replenishing on a human timescale. Hydropower, biomass, wind, solar and geothermal are the most commonly used forms of renewable energy, however, collectively make up only 10% of the world’s total primary energy consumption (BP, 2017). It is a challenge for many industries to shift away from fossil fuel consumption due to its low cost and energy alternatives are not always readily available. For instance, hydropower is a reliable energy source that has been used for decades at utility scale, however implementation is dependent on available resources and environmental implications. Furthermore, wind and solar energy have better potential to be modularized, but the cost of energy for these technologies has only started to become competitive with fossil fuels, and due to their intermittency, are unable to continuously produce energy to provide baseload. Therefore, greater effort is needed to increase the share of renewable energy in the primary energy supply through innovative solutions and lower costs.

Remotely located industries and communities can benefit from substituting fossil fuels with renewable energy sources for power generation. Areas that do not have access to a regional electrical transmission system must rely on their own means to generate electricity, which most commonly comes in the form of diesel generators. Due to its energy intensive nature, any mining operating based in a remote, off-grid area will demand large quantities of fuel to generate its own power. However, this creates a significant economic and environmental burden, as imported fuel is costly, and emissions associated with fuel combustion can be substantial. Therefore, there is a strong rationale for remote mining
operations to investigate alternative energy technologies that lower both the operating cost, due to reduced reliance on imported fuel, and environmental footprint.

It is becoming more common in remote areas to use hybrid renewable energy systems (HRES) to partially or fully offset fossil fuel consumption for electrical power generation. HRES can be grid connected or standalone, and consist of a combination of energy technologies such as renewable energy sources, conventional fossil fuel generators and energy storage. Furthermore, natural gas is considered a transition fuel, given its lower carbon intensity with respect to higher emitting carbon based energies like coal and oil. Common practice within the mining industry has historically been to favor diesel generators over ones fueled by natural gas. This is chiefly due to lower capital and fuel costs for the diesel option. However, natural gas emits less carbon dioxide (CO2) during combustion, and over recent years, natural gas prices have fallen, making gas generators an economically competitive option. Therefore, in this thesis natural gas generators will be considered as an alternative energy source, capable of providing reliable power.

1.1 Motivation

Significant political events, driven by the anticipated effects of climate change, have spurred the creation of global initiatives and climate policies for many nations. Notable events include the 1992 Kyoto Protocol, and more recent 2016 Paris Agreement. The Kyoto Protocol was the first international treaty to acknowledge that anthropogenic emissions are the primary cause of high levels of greenhouse gases in the earth’s atmosphere and need to be controlled (United Nations, 1998). The treaty also set internationally binding GHG emission reduction targets on participating countries. The Paris Agreement meanwhile, builds on established IPCC conventions by aiming to keep global temperature rise to well below 2°C and pursue efforts to limit the temperature increase to 1.5°C below pre-industrial levels (United Nations, 2015). The agreement requires participating countries to submit nationally determined contributions (NDC), which are documents outlining a country’s intended efforts to achieve their respective GHG emission reduction targets. As a result, many countries now have ambitious climate policies aimed at improved energy efficiency and greater renewable energy adoption. As part of Canada’s NDC submitted in 2017, the country intends to reduce GHG emissions by 30% below 2005 levels by 2030 (Government of Canada, 2017). Canada intends to meet this target through various initiatives such as pricing carbon pollution and complementary mitigation actions in the form of regulation and investment. Following their recent NDC submission, the Canadian government announced that a national carbon tax will be imposed on all provinces and territories that do not have a carbon pricing mechanism in place by the start of 2018. The carbon tax is expected to increase incrementally each year by C$10/tonne, until 2022 where it will reach C$50/tonne (Government of Canada, 2016). As of January 1, 2018, not all Canadian provinces and territories have carbon pricing mechanisms in place (including the Yukon territory), and the Canadian government has proposed a timeline for those jurisdictions not yet in compliance. As stated by the Environment and Climate Change Minister, Catherine McKenna, provincial and territorial governments have until March 30, 2018 to decide whether they will implement their own carbon pricing mechanism, or if they wish to adopt the federal carbon tax approach (Environment and Climate Change Canada, 2017). It is expected that these parties will adopt a C$10/tonne carbon tax in the fall 2018, which will subsequently rise in 2019. Furthermore, those jurisdictions electing to initiate their own carbon pricing mechanism are required to outline how they will do so by September 1, 2018, and implementation to follow shortly afterwards.
Canada is divided into ten provinces and three territories, where most of the Canadian population lives in lower latitudes of the Canadian provinces, leaving the territories more sparsely populated. Figure 1.1 presents a map of Canada where the Yukon (YT), Northwest Territories (NT) and Nunavut (NU) constitute the northern territories. Furthermore, Figure 1.2 reflects the electricity generation profile for each province and territory. Here it is evident that a diverse range of energies are used for power generation depending on local resources, and in 2014, 80.3% of electricity generation in Canada came from non-fossil fuel sources (Natural Resources Canada, 2017a).

Although the Yukon has well established hydropower generation, the other two territories (Northwest Territories and Nunavut) are dependent on petroleum products for power generation. The conditions present in these territories reflects the high cost of developing local energy resources and constructing electrical transmission networks, relative to the small towns and industries served. Similarly, remote mining operations in Canadian provinces and territories that do not have grid connection potential are reliant on their own means to generate power, which is commonly petroleum based.

![Map of Canada](image)

Figure 1.1 Map of Canada showing provincial and territorial boundaries (Natural Resources Canada, 2017b)
According to a study conducted by the Government of Canada, it is reported that approximately 328 MW of fossil fuel-driven generator capacity is employed to meet the electricity demand of off-grid communities in Canada (Royer, 2013). Whereas, a typical large-scale underground copper mine could demand up to 55% of this national supply by itself, with 180 MW on-site power requirement (Smyth, 2015). There are many operating and prospective mining operations located in remote areas of Canada that require substantial standalone power generation. The Canadian mining industry has an opportunity to proactively decarbonize their operations by implementing alternative energy technologies, thereby creating social, environmental and economic benefits, and aligning their efforts with Canada’s GHG emission reduction targets.

The cost of power for some remote precious metal mining operations can account for more than 20% of all operating costs (Smyth, 2015). Therefore, the cost of electricity plays a role in determining a project’s mine life, by allowing for a longer mining horizon if the cost of energy is low, and lower grade ore can be extracted. Until recently, the cost of renewable energy, namely on-shore wind, PV solar and energy storage were not economically attractive options to replace conventional fossil fuel based power sources. Furthermore, mining operations require large quantities of reliable power to operate safely, which cannot be provided by any one intermittent renewable energy source alone. Therefore, not only does the cost of HRES need to be competitive with conventional power generation methods, but they also need to be reliable and ensure that the electrical power demand is always satisfied.

1.2 Purpose and Scope

This thesis aims to improve understanding of the technical and economic feasibility of employing HRES at remote locations that are inherently reliant on diesel fuel for power generation. More precisely, a case study will be presented for a remotely located potential
mining operation in the Yukon territory of Canada. It is expected that a mine will be
developed at this location over the next decade, however no mining infrastructure has been
developed to date. Several scenarios will be evaluated consisting of a combination of fossil
fuel generators using diesel and natural gas, wind turbines, photovoltaic (PV) solar panels
and energy storage. Optimization techniques will be used to determine the optimal
configuration of each scenario by minimizing the levelized cost of energy (LCOE) while
also ensuring that the electrical power demand is satisfied. Site specific climate data as well
as current energy technology cost information and performance characteristics will be used
as model inputs. The results will be validated using HOMER Pro microgrid software and a
sensitivity analysis will be performed to identify project risk. The mining industry can
reduce its environmental footprint while also improving project economics by implementing
alternative energy technologies. Given the global effort to reduce greenhouse gas (GHG)
emissions, this objective should be a high priority for mining companies and other remote
industries as climate policy tightens and society shifts towards a low carbon economy.

Sizing HRES is a critical task, since under sizing can result in inadequate power
generation, while over sizing can lead to excessive costs. Moreover, the design of these
systems depends on site specific conditions and available technology. It is anticipated that
HRES employed in remote industries or communities be partially or fully renewable energy
based, using fossil fuel generators for back-up or additional power generation if necessary.
For the anticipated mine electrical power demand, fossil fuel generators will be sized
accordingly to meet the entire load requirements in case of insufficient power from
renewable energy components. The objective of this thesis is to provide the participating
industry partner with a proposal for an alternative energy technology based power system,
yielding a lower LCOE, reduced fuel consumption and lower GHG emissions than
conventional diesel generators. The proposed methodology can then be applied to similar
remotely located mining operations, given site specific renewable energy resource data and
mining assumptions.

### 1.3 Outline of Thesis

The following sections of this thesis will be carried out thusly: Chapter 2 will provide
background information relating to the case study location and expected mining method.
Chapter 3 will review literature pertaining to mine power systems, HRES and existing
methodologies for conducting techno-economic assessments of similar nature. Chapter 4
will outline the methodology selected for this study, including meteorological data, system
modeling, LCOE and GHG emission calculations, scenario evaluation, validation and
sensitivity analysis. Chapter 5 will present the results of each scenario, summarizing fuel
consumption, GHG emissions and LCOE, including sensitivity analysis, and will
furthermore ensure model validity. Finally, Chapter 6 will conclude by proposing the most
suitable courses of action for the case study, based on technical and economic conditions, as
well as project sensitivities. The currency used herein will be expressed in Canadian dollars
(C$), using an exchange rate of 1.25 Canadian dollars to 1 United States dollar ($) as of
September 1, 2017.
Chapter 2

Background

The case study presented in this techno-economic assessment pertains to an advanced stage mineral exploration project in northern Canada. The mineral exploration and development company that this thesis was performed in partnership with will remained unnamed, and here forth be referred to as “the Company”. The Company holds land claims containing mineral deposits in the Yukon territory of Canada, and is conducting exploration activities to better define the mineral resource. It is likely that mining will commence in the future, and collaboration efforts were established to evaluate the feasibility of using alternative energy technologies at the future mining operation, in place of conventional diesel generators. Namely, a combination of renewable energy sources and natural gas generators, as natural gas generators are not industry standard, however emit less GHG emissions than their diesel counterparts.

The case study is located in a remote area in the Yukon territory, and is distant from any human inhabitancy. Figure 2.1 illustrates the geographic climate in the Yukon, where the total population is approximately 38,000; 27,000 of which resides in Whitehorse, the territory’s capital (Yukon Bureau of Statistics, 2017). Aside from the road network connecting towns and industrial areas (denoted in red in Figure 2.1), the existing electrical grid operated by Yukon Energy Corporation services only as far east as Ross River, and as far north as Dawson City. Whitehorse is the closest industrial hub to the case study location, and accessing the electrical transmission system has been determined to be economically infeasible.

The case study site is accessible by un-paved road; however, a river crossing is required to complete the journey. The river crossing is passable by barge during summer months and ice road during winter. In the fall and spring, the river becomes impassable for a varying number of weeks, as it begins to freeze and is unable to support road traffic directly. This is a key limitation for the case study since this could cause delays in delivery of fuel and supplies. Historic ferry open and closure dates indicate that the ferry begins operation near the end of May and ceases in the middle of October. The duration of river freezing in fall and ice break up in spring varies year-to-year, however five weeks of impassibility reflects typical worst-case conditions.

The project lies amid a mountainous region, having elevations ranging between 1175 m above sea level (a.s.l.) and 2100 m a.s.l. at higher elevations. Meteorological data is available from a weather station located on the project site, and is operated by the previous project owner. Data from this weather station is reported in hourly intervals, and monthly averaged temperature data for the three-year period between July 1, 2014 and June 30, 2017 is presented in Figure 2.2. Data from this period indicates that the average annual temperature is -2.3°C, with extreme minimum and maximum temperatures of -33.4°C and 21.5°C, respectively.
Figure 2.1 Yukon territory map of main towns and existing road network (Yukon Travel, 2017)

Figure 2.2 Average monthly temperature at case study site between 2014 and 2017 (Data for this figure was provided by the Company)
At this stage, no mining plans have been established for the mineral deposits, however a preliminary economic assessment is forthcoming and will include a preliminary mine design. Therefore, the Company has provided estimates for the future mine plan. It is expected that the mineral resource will be mined using underground extraction methods with a mining rate of 5,000 tonnes per day (tpd), for a duration of nine years. The ore will be processed on-site in a milling facility capable of crushing and grinding the ore, followed by further chemical treatment. The final concentrate produced on-site will contain moderately high-grade material that will be shipped via large trucks to a port facility on the western coast of North America, and then by freighter to a smelter in Asia. The Company estimates that the mine will have a connected load of 10,614 kW, which accounts for the power rating of all electrical equipment. Detailed equipment selection and power requirements have yet to be determined, therefore, this power demand estimate does not consider daily or seasonal load characteristics.
Chapter 3

Literature Review

The purpose of this literature review is to present published material that is relevant to this thesis, as well as to investigate previous work carried out for similar applications. Since the objective of this thesis is to assess the feasibility of using alternative energy technologies at a remote mining operation, it is important to understand both the underlying framework of current mine power systems, as well as to review the proposed alternatives. The following sub-sections will review typical mine power systems, hybrid renewable energy systems and existing methodologies for carrying out techno-economic assessments of similar nature.

3.1 Mine Power Systems

Mining operations are energy intensive, requiring electricity for heavy machinery, fuel for haulage and auxiliary services, and in most cases heating for on-site processes. The power demanded by a mine site is dependent on the type of mine. The main processes common to any mining operation are: mineral extraction, haulage, comminution (crushing and grinding) and chemical treatment. The way in which mines carry out these processes can vary, but this framework holds true for conventional mining operations. Mine power systems are designed case-by-case, as a direct result of the mining and milling equipment power requirements. The following resources have been identified as being helpful for mining engineers to understand the fundamentals of power systems in mining applications.

The “SME Mining Engineering Handbook”, edited by Peter Darling (2011), is a culmination of mining and mineral processing guidelines commonly used within the mining industry. This textbook provides extensive reference material for each stage of the mining process, from exploration and mine planning, to mineral extraction and processing. It also includes sections pertaining to economics, health and safety, environmental issues, and community and social issues. The “Electric Power Distribution and Utilization” section contained within “Chapter 9: Infrastructure and Services”, offers a general overview of power distribution in mining (Darling, 2011, pp. 683-704).

Darling provides insight towards the nature of electrical power systems in mining, such as it being partly stationary, partly mobile, and electrical loading is often cyclic and variable (Darling, 2011, p. 683). For scale, he estimates that a typical 100,000 tpd mine and concentrator plant (mill) requires approximately 120 MW of power, and that power distribution lines need to be constructed for new mining customers (Darling, 2011, p. 683). However, grid connection is dependent on the remoteness of the mine, as well as available capacity on the existing electrical transmission system.

This handbook provides useful electrical terminology, which complies with the Institute of Electrical and Electronic Engineers standards. Demand is defined as the “electrical load for an entire complex or a single piece of equipment averaged over a specific time interval” (Darling, 2011, p. 684). Darling states that the engineer’s goal is to provide an efficient and reliable electrical system at maximum safety and for the lowest possible cost. The design is
subject to mine size, type of equipment used, haulage methods, anticipated expansion, available power from utility and the amount of capital assigned for the electrical system. He stresses that no two mines are exactly alike, therefore there is no standard power system.

The “SME Mining Engineering Handbook” provides a general overview of the mine electrical power system, and useful design considerations for mining and electrical engineers. Although many of the suggested principals should be adhered to for all mines, it does however place an emphasis on grid connected mines. That is, those that have access to a regional electrical transmission system and are not reliant on their own means for power generation.

Another handbook commonly used by mining engineers is the “Hard Rock Miner’s Handbook”, written by Jack de la Vergne (2000). Like the “SME Mining Engineering Handbook”, it reviews all mining aspects, however offers a more comprehensive guide to design. For example, the primary means of information exchange within this handbook is through rules of thumb, tricks of the trade, case studies and example problems. Unlike the prior handbook, the “Electrical” chapter in the “Hard Rock Miner’s Handbook” provides estimates for power consumption as a function of mining rate, and mining and processing method (de la Vergne, 2000, pp. 302-319). For example, the rule of thumb for power consumption of a typical underground mine, including mill will be approximately 100 kWh per tonne mined and processed (de la Vergne, 2000, p. 302).

De la Verne’s handbook also defines common electrical terminology as well as power laws and formulas. To estimate the power demand for a new mine, a common practice is to assume that the power required by all individual loads will be the nameplate capacity rating multiplied by a load factor and utilization rate. Where the load factor is the ratio of the running load divided by the nameplate power rating, and utilization rate is defined as the per unit running time divided by per unit time (de la Vergne, 2000, p. 220). The “Hard Rock Miner’s Handbook” contains a worked example of the estimated power consumption for a 2,500 tpd underground mine, not including mill. It tabulates all expected loads for such an operation and employs the definitions presented above to determine the monthly electricity consumption. De la Vergne also provides typical power consumption values for a mill, depending on ore type and mining method (underground (U/G) or open pit (O/P)), Figure 3.1 presents these findings.

![Typical Mill Power Consumption for Different Ore Types](image_url)

Figure 3.1 Typical mill power consumption for different ore types (de la Vergne, 2000, p. 310)
For a more comprehensive understanding of the power consumption breakdown within a mining operation, de la Vergne’s estimations will be further analyzed. De la Vergne’s underground mining electricity demand estimate will be delineated by main power consuming activities and used in addition to his mill power estimation for a Pb-Zn ore type. Figure 3.2 illustrates the results of this exercise, where it is evident that the mill is the primary power consumer, followed by the main access area (hoist) and ventilation. It should be noted that not every underground mine uses a hoist to transport personnel and materials from surface to underground, and a decline access ramp is commonly used instead.

Figure 3.2 Electrical power consumption breakdown for Zn-Pb underground mine and mill

The “SME Mining Engineering Handbook” and “Hard Rock Miner’s Handbook” complement each other by providing mining engineers with an improved understanding of mine power systems, in terms of required components and configurations, as well as design and sizing guidelines. However, to reiterate, designing power systems for mining operations depends on several factors, and ultimately is done in conjunction with preliminary mine and mill design. For a more practical assessment, the final paragraphs of this section will investigate power generation methods at existing mining operations in northern Canada.

There are many operating mine’s in northern Canada that serve as a basis for understanding modern mine site power demand and generation methodology. Most of these operations are remote and rely on diesel generators for electricity generation. Data was obtained from technical reports for 13 different mining operations, specifying mining rate, ore type, mining method, installed power capacity and power generation method. Data for all 13 mines is presented in Appendix A, however only four mines were selected for further analysis. These mines best reflect the conditions present at the prospective mine used in the case study, with exception to the type of ore mined, which varies for each mine. Each of the selected mines employ an underground mining method with an on-site mill, and are not grid connected. Figure 3.3 shows the results of this study, where the mining rate is plotted against installed diesel power capacity. Two of the four mines employ wind energy to generate electricity, however this additional capacity was not included in the analysis. Doing so would inflate the required power capacity, as mining operations ensure that enough diesel power capacity is installed so to make up for any short comings from the intermittent renewable energy components.
There is a trend between the collected benchmarked data points, however it should be stressed that given different operating conditions, deviation from this trend is to be expected. Furthermore, it is common practice to install additional power capacity than what is required. This is done to account for a safety factor or N+2 redundancy condition. The N+2 condition reflects that operation and maintenance activities will require taking at least one generator offline at a time and at least one additional unit is held in reserve for other unpredicted power failures. Therefore, the installed diesel capacity presented in Figure 3.3 does not reflect expected power demand for these mine sites, but also accounts for additional backup units to ensure safe operation.

### 3.2 Hybrid Renewable Energy Systems

The next topic to be presented in this literature review pertains to hybrid renewable energy systems. It is the objective of this thesis to determine the techno-economic feasibility of replacing the conventional mining power system with HRES, by harnessing local renewable energy resources and using alternative energy technologies. The following paragraphs will provide an overview of HRES, including examples of HRES in the mining industry.

A research study carried out by Ibrahim, Khair, & Ansari, titled *A Review of Hybrid Renewable Energy Systems for Electric Power Generation* (2015) provides an overview of HRES, including advantages and weaknesses, as well as design principals. Ibrahim and his colleagues define these systems as being “composed of one renewable and one conventional energy source or more than one renewable with or without conventional energy sources, that works in standalone or grid connected mode” (Ibrahim, Khair, & Ansari, 2015, p. 42). The intermittency of some renewable energy sources poses a potential setback for providing a continuous supply of electricity. However, integrating one or more renewable energy technology, with or without a conventional energy source can help to overcome this issue. The authors also state that the high capital cost of these systems is a deterring factor for implementation. Though, the high cost of grid connection and imported fuel in remote areas, can make HRES a competitive alternative.

The study proposes design considerations for the selection and sizing of HRES. The
authors suggest that the first step taken should be to determine the type of renewable energy technology to be included in the system, depending on available resources. This is followed by deciding on the quantity and capacity of each component, which can be done using optimization techniques to minimize system cost and emissions, or to maximize system reliability. The designer then needs to determine if a back-up generating unit and/or energy storage component is required.

The advantages of HRES, as listed by Ibrahim and his colleagues, are that these systems take advantage of the complementary nature of various renewable energy sources, have lower emissions than conventional energy sources, and achieve an acceptable cost, due to optimal design configuration. One common disadvantage for HRES is that they often require an energy storage component, which can be costly due to monitoring and future replacement. Furthermore, erratic changes in weather conditions can affect HRES power output and system stability. Therefore, including a weather independent power generation component, like a fossil fuel generator can ensure reliability.

Using renewable energy for power generation at mining operations is not an unheard-of concept within the mining industry, and there are several cases where PV solar arrays and wind turbines have been employed for such purposes. A recent study conducted by (Choi & Song, 2017) titled Review of Photovoltaic and Wind Power Systems Utilized in the Mining Industry provides a list of global examples where renewable energy is used at mining operations. Based on the author’s findings, the primary forms of renewable energy being employed in large quantities is PV solar and onshore wind energy. The following examples have been obtained from Choi & Song’s study and pertain to large scale PV solar and wind power generation used in the mining industry.

PV solar panel facilities are used in several arid mining regions around the world, most notably in Australia, Chile and in the United States. DeGrussa and Weipa mines in Australia have integrated 10.6 MW and 6.8 MW PV solar arrays with their mine’s power systems, respectively. Both mines also employ diesel generators for their remaining electrical demand, and the solar installation at Weipa offsets approximately 20% of diesel fuel consumption. Chuquicamata, the world’s largest open pit copper mine, is in the middle of the Atacama Desert (Chile) and experiences some of the highest levels of solar radiation in the world. Since 2011, it’s 1 MW PV solar array produces approximately 2.69 GWh of electricity, annually. Similarly, the Goldstrike mine located in Nevada, USA, has a 1 MW PV solar installation, taking advantage of the area’s hot and dry climate.

Wind integrated systems are less common in the mining industry, however there are two mines in northern Canada that have integrated wind energy in their standalone power systems. Diavik diamond mine, located in the Northwest Territories, has installed 9.2 MW of wind power, producing 17 GWh of electricity each year, and offsetting approximately 10% of the site’s diesel consumption (Yip & Pollock, 2017). Meanwhile, the Raglan mine, located in northern Quebec has implemented a pilot-scale wind energy system. One 3 MW wind turbine has been installed at the site, along with a combination of energy storage technologies including a flywheel, hydrogen electrolysis and battery storage units (Tugliq Energy, n.d.). Finally, a different approach is taken by Antofagasta Minerals, which sources grid connected wind energy to be used at its Los Pelambres mine in Chile. Antofagasta Minerals owns 30% of the 115 MW El Arrayán grid connected wind farm, and in turn allocates 70% of its energy production to be used at its mine through a fixed price agreement.

For many of the same reasons stated by Ibrahim and his colleagues (2015), Choi & Song (2017) demonstrate that there are a handful of remotely located mining operations beginning to implement renewable energy sources at their operations. Although, it is observed that many of these installations have low renewable energy penetration rates, and fossil fuel
based power generation continues to dominate their respective energy profiles. Furthermore, it is apparent that the type of renewable energy technology deployed depends on the regions climate, and meaningful reductions in fuel consumption is achievable with increased renewable energy implementation.

3.3 Techno-Economic Studies

Techno-economic studies are a common method to assess the feasibility of a new technology or practice, without undergoing high level design and analysis which is often required by a feasibility study. It is used as an efficient method to evaluate if a proposed solution is not only technically achievable, but also cost effective; and further work can be pursued if the technology or practice is considered promising. This section of the literature review will investigate common guidelines for conducting these types of studies, as well as presenting published material pertaining to HRES using a techno-economic format.

Maximilian Lauer published a report titled Methodology Guideline on Techno Economic Assessment (TEA) (n.d.). This report is intended to act as a tool for engineers carrying out research and development, by proposing a consistent and transparent framework for conducting techno-economic assessments. The main components of Lauer’s framework are cost, benefit and risk assessment, and Lauer states that these types of studies can be used to meet different objectives.

There are several approaches that can be used when undertaking a techno-economic assessment, where common cost metrics include net cashflow, net present value and internal rate of return; all of which can be accompanied by a sensitivity analysis. According to Lauer, optimization techniques appear to be the prevailing method for carrying out techno-economic assessments. However, since there are many different optimization techniques available, selection depends on several problem specific factors. Messac, the author of Optimization in Practice with MATLAB: For Engineering Students and Professionals, defines optimization as “the process of maximizing and/or minimizing one or more objectives without violating specific design constraints, by regulating a set of variable parameters that influence both the objectives and the design constraints” (Messac, 2015). Applying this definition to HRES, a system metric like energy cost or GHG emissions is minimized by manipulating design variables such as number of wind turbines or PV solar panels, such that design constraints are not violated. The studies presented below use a similar framework as the one proposed by Lauer and employ a variety of optimization techniques and system modeling methodologies. These studies reflect current practices for sizing HRES.

The first techno-economic study presented is titled Techno-Economic Optimization of Hybrid Photovoltaic/Wind/Diesel/Battery Generation in a Stand-Alone Power System by Kaahebe & Ibtious (2014). This study was selected because it evaluates scenarios like the ones involved in this thesis and the optimization approach is not overly complex. Three scenarios are compared: PV/wind/diesel/battery, PV/wind/battery and diesel only. The system is optimized for a single objective, minimizing the energy cost by using an iterative approach. Electricity demand, solar radiation, ambient temperature and wind speed data was collected from a site in Algeria and used as a case study. The diesel component is sized to meet peak demand, while the number of PV solar panels and wind turbines are varied systematically. The system is modeled using design equations for each component and the optimization performs calculations for all possible combinations.

The study’s results compare the optimal configuration and energy cost of each scenario, as well as fuel consumption and CO₂ emissions associated with the diesel component. The
scenario yielding the lowest energy cost is the hybrid PV/wind/diesel/battery system ($1.30/kWh), while the diesel only system yields the highest energy cost ($1.60/kWh) and annual CO₂ emissions. The intent of the work carried out by Kaabche & Ibtouen was to grow a global methodology for HRES sizing optimization.

The next study presented aims to optimally size a similar hybrid PV/wind/diesel/battery system, however considers multiple component sizes and proposes a multi-objective framework to minimize both LCOE and life cycle emissions (LCE). The work carried out by Dufo-López and his colleagues in the study titled Multi-Objective Optimization Minimizing Cost and Life Cycle Emissions of Stand-Alone PV-Wind-Diesel Systems with Batteries Storage (2011) selected two case study sites, both located in Spain, representing different climate conditions. For each site, the same two daily load profiles were used, one that is constant and one that represents typical household demand. One PV solar panel model was considered, along with three wind turbine models, two battery models, two diesel generators, two gasoline generators and two inverter models. The constraints set for the optimization are 0 to 2 wind turbines, 0 to 20 PV solar panels, 0 to 10 batteries and 30% minimum power output from the diesel or gasoline generators.

Due to system complexity, the authors used genetic algorithms to determine optimum system configurations and presented their results using pareto fronts. Pareto fronts are a common way to illustrate multi-objective optimization results, since the nature of multi-objective problems have conflicting objectives. In other words, unless a weighting factor is used the optimal configuration will be at the user’s discretion, depending on whether they favor low LCOE or LCE. The study results confirmed the author’s assumption that each location will use different system configurations given their respective climates. A sensitivity analysis was also conducted, which varied the inflation rate, acquisition costs and emission rates. This research paper proposed a robust methodology for carrying out a HRES techno-economic assessment, as it considered multiple objectives and component sizes.

The next research study to be reviewed takes a different sizing approach than the previous studies as it employs HOMER Pro, a publicly available microgrid design software. In the study titled Techno-Economic Feasibility of Photovoltaic, Wind, Diesel and Hybrid Electrification Systems for Off-Grid Rural Electrification in Colombia (2016) Mamaghani and his colleagues undertake a thorough case study for three remote areas in Colombia, analyzing multiple configuration scenarios, along with multiple technology sizes. Two PV solar panel models, two wind turbine models, two battery models, one inverter and one diesel generator were selected for the analysis. The authors used national solar and wind atlas data to obtain monthly averaged solar radiation and wind speed values for each site, and prices for system components were obtained from local distributors. HOMER produced three economic indicators for each scenario: total net present cost, cost of energy, and capital cost. The optimal configuration for two of the chosen locations included solar and diesel, while for the third consisted of solar, wind and diesel. The energy cost for each site’s optimal configuration was similar, and the electricity generated by renewable energy exceeded 98% for each location.

Although the previously described techno-economic studies pertain to the electrification of remote houses or communities, none have addressed remote mining operations. A recent study carried out by Vyhmeister and his colleagues, titled A Combined Photovoltaic and Novel Renewable Energy System: An Optimized Techno-Economic Analysis for Mining Industry Applications (2017) addresses this application, by using the mining industry in the Antofagasta region of Chile as a case study. The authors acknowledge that the Chilean mining industry is the country’s main economic driver and one of the main energy consumers, due to the high levels of energy required to process ore as well as de-salinate
ocean water for its operations. As the country looks to reduce GHG emissions, it must start using alternative low carbon emitting energy technologies. The proposed HRES consists of a PV solar array, as well as a novel wind energy technology that aims to collectively supply at least 10% of the mine’s current and future electrical power demand. Electricity produced from both technologies would be supplied to the regional electrical grid, which in turns supplies electricity to the mining operations in the region.

The techno-economic methodology employed by the authors is similar to previous studies: the system is modeled using MATLAB, and cost information, in terms of capital and operating costs are collected for each technology. The net present value for the entire project is minimized using constrained, non-linear optimization techniques to determine the optimal number of wind energy units and PV solar panels to be used. The authors apply a 3.8% growth rate to annual electricity demand; therefore, additional wind energy units and PV solar panels are required each year. Monthly solar radiation, temperature and wind speed data is used for the analysis. The study results indicate that the proposed HRES is close to being competitive with existing electricity rates, where the combined LCOE for wind and solar power is $0.255/kWh, compared to the average regional electricity cost of $0.2/kWh.

To briefly summarize published research studies pertaining to techno-economic assessments of HRES, each study sizes the desired system using optimization techniques, where cost minimization is the primary objective. The studies presented in this literature review provide a small representation of the extensive published material in this field. The sizing methodology varies and appears to depend on the researcher’s goals, aims and desired system complexity. Furthermore, there is also published material solely devoted to cataloguing historic techno-economic assessments for HRES. In this way, interested parties can efficiently review published work relevant to their research and use it as a reference guide. A common theme of HRES techno-economic assessments pertains to using novel approaches and tailoring optimization techniques to better serve the researcher’s objectives. While a growing number of researchers are beginning to utilize available design software, to aid in computation.
Chapter 4

Methodology

The previous chapters of this thesis were dedicated to addressing conventional energy sources used in the mining industry and reviewing available literature and methodologies for conducting techno-economic assessments of hybrid renewable energy systems. The following chapters will offer original research relating to the case study described in Chapter 2, where this chapter presents the methods taken to fulfill this thesis’ objectives. The themes described in this chapter form the basis for determining the feasibility of using alternative energy technologies at a remote mining operation in the Yukon territory of Canada.

The first section in this chapter examines case study specific meteorological data to identify local wind and solar energy resources. The next section involves modeling the proposed power system based on technical and economic parameters for each component. Common energy metrics such as levelized cost of energy and GHG emission rates will be discussed, since these definitions help define the power system value. The following section addresses evaluation methods used to perform simulation and analysis. Due to the anticipated fuel supply interruption occurring twice yearly, dedicated natural gas generators are deemed unsuitable for this case study since prolonged gas storage is costly and presents safety concerns. Therefore, dual fuel generators, capable of substituting up to 70% of diesel fuel with natural gas or using 100% diesel, will be targeted as the alternative substitute for diesel generators. Several scenarios constituting different power system configurations will be investigated and are summarized as follows:

1. Diesel generators (base case)
2. Dual fuel generators
3. Dual fuel generators and wind turbines
4. Dual fuel generators and PV solar panels
5. Dual fuel generators, wind turbines and battery storage
6. Dual fuel generators, PV solar panels and battery storage
7. Dual fuel generators, wind turbines, PV solar panels and battery storage

Each configuration will be modeled and simulated for a sample year to quantify the system cost, fuel consumption and GHG emissions of each arrangement. The remaining sections in this chapter pertain to validating the results using a common HRES design software and evaluating project risk through a sensitivity analysis.

4.1 Meteorological Data

To understand the renewable energy potential for a given location it is important to consider local meteorological conditions. This thesis aims to evaluate the techno-economic feasibility of using wind and solar energy at a prospective mining operation in a remote area of the Yukon territory. Therefore, climate data affecting wind turbine and PV solar panel electrical
power output must be gathered and analyzed. Accurate and complete data is critical for providing meaningful results, and the data used should reflect typical conditions experienced at the region of interest. Hourly data collected over an entire year (or multiple years) provides good resolution to simulate accurate meteorological conditions. The following paragraphs will review the area targeted for renewable energy development and sources of data pertaining to wind and solar energy resources.

As described in Chapter 2, the case study lies amid a mountainous region, therefore, elevations vary considerably and there are few large and flat open spaces, which are necessary for wind and solar energy projects. An aerial view of the project site is presented in Figure 4.1, where the prevailing valley and steep slopes are demonstrated. Experts at the Company have identified one area as being most suitable for renewable energy development. This is a large plateau, at an average elevation of 1750 m a.s.l, and the areas designated for wind and solar energy development are shown in Figure 4.1. Since most flat areas near the project site are found in low lying valleys, these areas yield low wind speeds and abundant shading from nearby mountains. Alternatively, the space available on the plateau is at a much higher elevation, resulting in reduced shading and greater solar radiation. Furthermore, wind speeds are greatest and most consistent at this location. The wind area is small in comparison to the solar area as wind speeds further south of the designated wind area are lower.

![Aerial View of Case Study Site](image)

**Figure 4.1 Arial view of wind and solar areas near case study site**

An accurate resource assessment for any renewable energy technology is vital for estimating future performance and energy output. Meteorological weather stations installed at the region of interest can provide accurate data to conduct these assessments. Unfortunately, this type of data is not always readily available as weather stations can be costly and the desired location may have limited existing infrastructure. To combat this issue, a few options exist to provide an indication of local resource quality, and are as follows:

- Resource maps or satellite databases
- Nearby weather stations
- Commercially available datasets
Each of these options lack the precision required for a detailed feasibility study, however can form the basis for preliminary estimation and planning. Resource maps or satellite databases are publicly available resources that can often provide average monthly and/or daily meteorological information. Alternatively, data collected by nearby weather stations can provide a suitable alternative to gauge historic weather data in the broader area. Additionally, several companies offer commercial solutions to help overcome the issue of acquiring data for a precise location. Their services usually include modeling local climate conditions and providing time series datasets of desired resolution. Local weather station data and commercial solutions will be pursued further for wind and solar energy resource evaluation in this thesis.

### 4.1.1 Wind Energy

A wind resource is best evaluated at the expected wind turbine hub (component linking rotor blades and housing the gearbox and generator) height, often in the range of 40 to 100 m above ground level. However, the case study site does not yet have a meteorological weather station installed to record data from comparable heights. A provider of time series data for wind turbine applications is AWS Truepower. AWS Truepower provides several services including resource assessments, feasibility studies, permitting support and environmental assessments. The wind resource data that AWS Truepower provides uses microscale and mesoscale modeling to produce typical year virtual met masts (TY-VMM) time series files with heights above ground level ranging from 10 to 140 m. Through an academic agreement, AWS Truepower provided hourly time series data for the targeted area. The data includes temperature, pressure, wind direction, wind speed, air density and turbulence intensity for an entire year at heights of 20, 40, 60, 80 and 100 m above ground level. Figure 4.2 illustrates the targeted area for wind turbine development. The extent of this area, as seen in Figure 4.1, is 1.9 km by 0.2 km, for a total area of 0.4 km².

![Figure 4.2 View of targeted area for wind turbine development on top of plateau, looking north-west](image)
Wind speed time series data at 70 m above ground level obtained from AWS Truepower is illustrated in Figure 4.3, where hourly data begins on January 1. The data exhibits seasonality, where wind speeds appear to be greatest in the winter and lowest during summer. The average annual wind speed at 70 m above ground level is 5.2 m/s. Diurnal average wind speed values are also presented in Figure 4.3, where wind speeds appear to be greatest in the morning hours. Furthermore, the wind rose for the collected data is presented in Figure 4.4, where the prevailing wind direction blows from the south. Temperature in this dataset ranges between -39.9°C and 19.3°C, however historic temperatures for this area have fallen below -40°C. This is an important consideration since below -40°C, most commercially available wind turbines cease operation.

An additional factor that should be considered in cold climates is the formation and extent of icing conditions. Buildup of ice on wind turbine components, especially rotor blades may cause early wear-and-tear, primarily due to increased fatigue loading. Therefore, if icing conditions are expected, preventative measures should be taken, by means of anti-icing turbine technology, which can increase wind turbine costs. The temperature range where icing can occur is below 0°C, however icing conditions are not exclusively a function of temperature (Frohboese & Anders, 2007). Other factors that influence ice buildup such as precipitation rate, wind speed, liquid water content and water droplet size are not easily recognized without sensors and a good understanding of local meteorological conditions. However, a preliminary estimate of icing accumulation can be made by visual inspection during winter months and failure of other sensory equipment.

Figure 4.3 Hourly (left) and diurnal (right) wind speed time series data at 70 m above ground level
4.1.2 Solar Energy

Photovoltaic solar panels convert light emitted by the sun into electrical energy and solar radiation is a distinguishing metric for characterizing solar resources. In addition to solar radiation, several factors can affect the performance of a PV solar panel array, such as ambient temperature, shading, dust and dirt accumulation and snow loading. Therefore, the ideal placement of solar power installations should receive high levels of solar radiation year-round with minimal shading, snowfall and dusty conditions. The Yukon territory receives low levels of solar radiation and a substantial amount of snowfall when compared to climates at lower latitudes. However, solar energy projects are not unheard of in arctic climates and will therefore be considered for this project. For example, small solar panel installations have been implemented at the Fort Simpson Education Complex in the Northwest Territories, as well as at the Yukon Energy main administration building in Whitehorse, to name a few. The space available for PV solar panel installation is more expensive than for wind turbines, as aside from shading, adjacent solar panels do not reduce the quality of solar resource. Whereas wind turbines produce downstream and adjacent turbulence through wake generation and need to be spaced accordingly. Figure 4.5 outlines the potential area available for PV solar panels, which is adjacent to the area designated for wind turbines, however continues further south. The extent of this area, as shown in Figure 4.1 is 1.2 km by 0.6 km, for a total area of 0.7 km².
Unlike characterizing a wind resource, solar resource evaluation is less dependent on micro-siting, and can be evaluated for broader areas. Local meteorological weather stations within a short distance from the region of interest can be used for this purpose, as the magnitude and profile of solar radiation is not expected to significantly change. Fortunately, the previous project owner, installed a weather station located approximately 600 m from the targeted area for PV solar panel development, at 300 m decreased elevation. The weather station, as depicted in Figure 4.6, collects hourly averaged rainfall, pressure, wind speed, gust speed, wind direction, solar radiation, temperature and relative humidity data. A pyranometer measures the total solar radiation on a flat surface and is the sum of beam and diffuse solar radiation (also referred to as global horizontal irradiance).
The time series data collected by this weather station has been provided by the previous project owner and solar radiation values for the year 2016 are presented in Figure 4.7, where hourly data begins on January 1. There is inherent seasonality present in solar radiation, both on an annual and daily timescale. For example, solar radiation will be strongest during the day and summer months, whereas it will be significantly lower, if not close to zero at other times. The diurnal average values for the sample year are also illustrated in Figure 4.7. The average solar radiation received by the weather station for the sample year is 92 W/m².

![Hourly Solar Radiation Data](image1)

![Diurnal Average Solar Radiation Values](image2)

Figure 4.7 Hourly (left) and diurnal (right) solar radiation data collected from weather station

### 4.2 System Modeling

The purpose of modeling the proposed power system configurations is to provide an accurate estimation of power produced by each component, and a basis for evaluating system cost, fuel consumption and GHG emissions. A typical year will be simulated using hourly time series data for meteorological conditions and power demand. Time series data from the year 2016 will be used for the analysis, therefore 8784 hours will be simulated, as 2016 was a leap year. To quantify power generated from each component, design equations and necessary assumptions will be described for wind turbines, PV solar panels, Li-ion battery units and fossil fuel generators. Technical constraints such as wind turbine spacing and available area designated for renewable energy development will also be considered. Once the system is modeled and simulated in MATLAB, evaluation methods will be used to size the renewable energy components by minimizing LCOE for each configuration.

Figure 4.8 presents the configuration of the proposed power system for the scenario where all components are connected to the load. The mine load in this figure is represented by a ball mill and ventilation fans, since the mill and ventilation are the primary power consuming activities for an underground mine (without hoist). For simplicity, one alternating current bus bar is used to connect power generation components with mine loads via central substation. However, in practice it is expected that an extensive network of electrical cable and other power system infrastructure be developed to deliver electricity to mining equipment. Voltage and current conversion devices are assumed to be implicit with each component. Furthermore, inverters are required for PV solar panels and battery units, as these components use direct current. While the other components and loads are expected to generate and consume alternating current. Inverter costs and efficiencies are included in cost estimations for PV solar panels and battery units.
4.2.1 Mine Power Demand

Prior to modeling power system components, it is important to first consider the expected power demand. Although it is common in most techno-economic studies to consider varying power demand on an hourly and seasonal basis, mining power demand is relatively constant over the duration of a year. This is due to large power consuming activities, such as mineral processing and ventilation requiring a continuous supply of power over the project life. With exception to increased mining and processing rates, as well as scheduled or unscheduled maintenance downtime. Another factor affecting power demand is ambient conditions around the mine site, as well as the cyclic nature of some mining equipment. Particularly for underground mines, air provided to the underground workings by a ventilation network needs to be preheated in cold climates, which may cause a seasonal shift in power consumption. Furthermore, there are several underground mining processes, as well as on-site infrastructure that require power and do not operate continuously. Therefore, these processes could affect the daily load requirements for mining operations.

As depicted in Section 3.1 of the literature review, the main power consuming activities for a typical underground mine are the mill, main access and ventilation, with the underground power requirement making up a small fraction of demand. Therefore, it is assumed that cyclic mining activities occurring underground will have minimal effect on the overall power demand of the mine, and mining processes with relatively fixed power

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1 References for images (clockwise from top right): (Electrovaya, 2016), (Metso, 2017), (ACTOM, 2016), (REC Group, n.d. (a)), (EWT, 2017), (Generac Power Systems, 2017)
demand will dictate power consumption. Therefore, a constant hourly power demand will be used in this study. Following a preliminary estimate conducted by the Company, the expected connected load is 10,614 kW. Accounting for 366 days in the sample (leap) year, along with a load factor of 80% and utilization rate of 92%, the expected annual electricity consumption is 68,620,000 kWh. Therefore, an hourly power demand of 7,812 kW, representing mean power demand, will be used for subsequent analysis.

4.2.2 Wind Turbines

There are many wind turbine manufacturers and models available, where suppliers offer wind turbines that range in size and technology. For example, Siemens’ current offerings of on-shore wind turbines include direct drive and geared wind turbines, ranging from 2.3 to 4.3 MW. By comparison, Enercon provides a slightly wider portfolio of wind turbines ranging from 800 kW to 4.2 MW. Selecting the appropriate wind turbine model depends on the available wind resource, desired power output and to some extent, purchaser’s preferences. For this study, Netherlands based wind turbine manufacturer, EWT was contacted and provided relevant wind turbine technical and economic data. EWT specializes in direct drive wind turbines and has experience installing wind turbines in North America, including northern Canada. EWT offers wind turbines ranging from 250 kW to 1.0 MW.

EWT estimates that the all-in capital cost including cost of turbine, transportation and installation in the Yukon territory is C$2 million per wind turbine, with an annual operating cost of C$40,000. These costs are assumed to be fixed for each wind turbine model, as EWT’s wind turbine offerings are of comparable sizes (similar hub heights), where the main difference is rotor diameter. Furthermore, due to the remoteness of the case study location, transportation and installation costs make up a large part of the wind turbine’s capital cost, and expected to be fixed regardless of wind turbine model. Since the capital cost is fixed for each wind turbine offered by EWT, the 1.0 MW model has been selected for further analysis, as this model has the lowest energy cost with respect to the smaller models. Table 4.1 outlines the technical parameters for this wind turbine model. Larger utility scale wind turbines were not pursued further in this case study, as it is expected that the capital cost for 3+ MW wind turbines increases substantially, and delivery and installation of larger models could pose logistical issues.

<table>
<thead>
<tr>
<th>Model</th>
<th>Rated Power (kW)</th>
<th>Rotor Diameter (m)</th>
<th>Hub Height (m)</th>
<th>Rated Wind Speed (m/s)</th>
<th>Cut-in Wind Speed (m/s)</th>
<th>Cut-out Wind Speed (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DW61-1.0 MW</td>
<td>1,000</td>
<td>61</td>
<td>69</td>
<td>14</td>
<td>3</td>
<td>25</td>
</tr>
</tbody>
</table>

A common practice to determine wind turbine power output is to use the wind turbine model’s power curve, provided by manufacturer. Figure 4.9 illustrates such a diagram for EWT’s DW61-1.0 MW wind turbine. There are four distinct zones in the power curve regarding power production. The first zone results in zero power output due to insufficient wind speeds, ranging from zero to a cut-in wind speed ($v_c$), or wind speed at which the wind turbine begins to generate power. The second zone describes increasing power output with respect to increasing wind speed. This zone begins at the cut-in wind speed and continues until the rated wind speed ($v_r$) is reached. The third zone ranges from the rated wind speed to the cut-out wind speed ($v_{co}$), where the wind turbine ceases to operate to prevent damage.
In this zone, the wind turbine generates its rated power capacity ($P_{r,WT}$) regardless of wind speed. The final zone occurs where wind speeds exceed the cut-out wind speed and the wind turbine power output is zero.

![EWT DW61-1.0 MW Power Curve](image)

Figure 4.9 Power curve for EWT DW61-1.0 MW wind turbine model (Data for this figure was provided by EWT)

As previously mentioned, the cut-in, rated and cut-out wind speeds are provided by wind turbine manufacturer, and are summarized in Table 4.1 for the selected wind turbine model. To mathematically model the power output of each wind turbine on an hourly basis, the piecewise function presented in Equation 1, describes the relationship between wind speed ($v$) and power output ($P_{WT}$) at time $t$. Where $q(v)$ defines the region of the power curve between the cut-in and rated wind speed. This region is not easy to define using a single equation, since the curve does not follow a simple regression. Therefore, a series of linear lines with 0.5 m/s resolution will be used to describe $q(v)$, the data of which has been provided by EWT.

$$P_{WT}(t) = \begin{cases} 
0, & v < v_{ci} \\
q(v), & v_{ci} < v < v_{r} \\
v_{r} < v < v_{co} \\
0, & v > v_{co}
\end{cases}$$

1

The annual electricity produced by the wind turbine(s) ($AEP_{WT}$) is calculated using Equation 2, where the wind turbine power output is added for each hour in the sample year and multiplied by the number of wind turbines installed ($N_{WT}$).

$$AEP_{WT} = N_{WT} \times \sum_{t=1}^{8784} P_{WT}(t)$$

2

The number of wind turbines used for this case study is dependent on the available area and spacing requirements. To prevent wake interference between wind turbines, common spacing recommendations are 3-5 times the rotor diameter in the inline direction and 5-10 times the rotor diameter in the downstream direction (Tester, et al, 2012). This means that a wind turbine with 61 m rotor diameter should maintain 244 m and 458 m spacing, inline and downstream, respectively. The area devoted to wind turbine development in the targeted
area is 1.8 km inline and 0.2 km downstream, as further downstream (south) the terrain becomes undulating and wind speeds decrease. Therefore, the maximum number of DW61-1.0 MW wind turbines is a single row of seven.

4.2.3 Photovoltaic Solar Panels

Manufacturers of PV solar panels offer a range of models that have varying rated power, efficiency, durability and quality. For utility scale applications, it is common to use panels with the largest rated power capacity available. Furthermore, for this case study, it is important to consider solar panels that can endure cold temperatures and other harsh climatic conditions. Canadian solar energy development company, Skyfire Energy was consulted for solar panel recommendations and advised that REC TwinPeak 2S 72 should be used for this project. Table 4.2 outlines physical properties and recommended operating conditions for this panel.

Table 4.2 PV solar panel physical parameters and operating conditions (REC Group, n.d. (b))

<table>
<thead>
<tr>
<th>Model</th>
<th>Dimensions (mm)</th>
<th>Area (m²)</th>
<th>Weight (kg)</th>
<th>Max Snow Load (kg/m²)</th>
<th>Operating Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>REC TwinPeak 2S 72</td>
<td>2005 x 1001 x 30</td>
<td>2.01</td>
<td>22</td>
<td>550</td>
<td>-40 to 85</td>
</tr>
</tbody>
</table>

Multiple capital cost estimates were acquired from industry contacts for PV solar energy projects ranging from C$1.8 to C$2.7 per W of installed power capacity. Estimates on the lower end of this range do not include installation and other extraneous costs. Therefore, C$2.7/W all-in capital cost estimate will be used for this study. The annual operating cost is expected to be C$10/kW of installed capacity.

To analyze how solar panels will perform under various conditions, two tests are performed, and results of which are included on manufacturer data sheets. Standard test conditions (STC) and nominal operating cell temperature (NOCT) are laboratory conditions that characterize solar panel performance. Table 4.3 summarizes the conditions at which both tests are performed for REC TwinPeak 2S 72 solar panel. In addition to these parameters, the relationship between cell temperature and solar panel power output is an important consideration. For the selected solar panel, the temperature coefficient of nominal power (α) is -0.36%/°C, which accounts for lower electrical power output as panels get hotter.

Table 4.3 Solar panel operating parameters under STC and NOCT (REC Group, n.d. (b))

<table>
<thead>
<tr>
<th>Parameter</th>
<th>STC</th>
<th>NOCT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal Power</td>
<td>350 W</td>
<td>259 W</td>
</tr>
<tr>
<td>Solar Irradiance</td>
<td>1000 W/m²</td>
<td>800 W/m²</td>
</tr>
<tr>
<td>Ambient Temperature</td>
<td>-</td>
<td>20°C</td>
</tr>
<tr>
<td>Cell Temperature</td>
<td>25°C</td>
<td>44.6°C</td>
</tr>
<tr>
<td>Wind Speed</td>
<td>-</td>
<td>1 m/s</td>
</tr>
<tr>
<td>Air Mass</td>
<td>1.5</td>
<td>-</td>
</tr>
</tbody>
</table>

PV solar panel power output will be calculated using hourly weather station data provided by the previous project owner. A simple method to calculate power output is to
assume a linear relationship between power output at STC ($P_{STC}$) and power output of solar panels ($P_{PV}$) with the total solar irradiance received on the panel surface ($G_T$) and solar irradiance at STC ($G_{STC}$). The effect of cell temperature ($T_c$) on power output is also accounted for using the temperature coefficient and cell temperature at STC ($T_{c,STC}$). Equation 3 presents this relationship, as adopted from Riffonneau and his colleagues (2011). Cell temperature is derived using ambient air temperature ($T_a$) and total solar irradiance, as well as solar irradiance, cell temperature and ambient air temperature at NOCT, $G_{NOCT}$, $T_{c,NOCT}$ and $T_{a,NOCT}$, respectively; Equation 4 demonstrates this relationship (Riffonneau et al, 2011).

$$P_{PV}(t) = P_{STC} \times \frac{G_T(t)}{G_{STC}} \times [1 + \alpha \times (T_c(t) - T_{c,STC})]$$  

$$T_c(t) = T_a(t) + \frac{G_T(t)}{G_{NOCT}}(T_{c,NOCT} - T_{a,NOCT})$$  

Annual electricity generated by the solar panel array ($AEP_{PV}$) is a function of individual panel power output, as calculated using Equation 3, and number of solar panels in the array ($N_{PV}$), expressed in Equation 5. The maximum number of solar panels that can be used is a function of available area and spacing requirements. The area targeted for PV solar panel development is 0.7 km$^2$, however there is flexibility in design and area devoted to the array.

$$AEP_{PV} = N_{PV} \times \sum_{t=1}^{8764} P_{PV}(t)$$

The power output calculated using Equation 3 assumes that solar panels track the sun’s movement throughout the day and receive maximum solar irradiance available. However, tracking systems significantly increase capital and operating costs, therefore fixed axis solar panels are being considered for this case study. Three different types of radiation will be considered for the calculation of total irradiance received by panels: beam, diffuse and reflected. Global horizontal irradiance measured by the pyranometer installed on the weather station accounts for beam and diffuse radiation, however does not include reflected radiation. Duffie and Beckman’s textbook titled “Solar Engineering of Thermal Processes” (2013) is a comprehensive guide to solar radiation and will be used as a reference for modeling the solar thermal processes that follow.

The angle and orientation of PV solar panels in addition to the sun’s position in the sky determines the magnitude of each type of radiation. Given the panel tilt angle ($\beta$), azimuth orientation ($\gamma$) and local latitude ($\varphi$), the incident angle ($\theta$), or angle between beam solar radiation and normal to the panel surface, can be calculated using Equation 6.

$$\cos(\theta) = \sin(\delta)\sin(\varphi)\cos(\beta) - \sin(\delta)\cos(\varphi)\sin(\beta)\cos(\gamma) + \cos(\delta)\cos(\varphi)\cos(\beta)\cos(\omega) + \cos(\delta)\sin(\varphi)\sin(\beta)\cos(\gamma)\cos(\omega) + \cos(\delta)\sin(\beta)\sin(\gamma)\sin(\omega)$$

Declination of the earth’s tilt with reference to the sun ($\delta$) can be calculated using Equation 7, where the Julian day number is expressed as an integer ($n$). The hour angle ($\omega$) is calculated using Equation 8 and the solar time ($t_s$) is calculated from Equation 9, using the local time ($t_l$), local longitude ($L$), standard meridian for local time zone ($L_m$), as well as $E$ and $B$, calculated using Equation 10 and Equation 11, respectively.
\[ \delta = 23.45 \sin(360 \frac{284 + n}{365}) \]

\[ \omega = 15^\circ \times (t_s - 12) \]

\[ t_s = t_i + \frac{1}{15}(L_{tx} - L) + E \]

\[ E = \frac{229.2}{60} (0.000075 + 0.001868 \cos(B) - 0.032077 \sin(B) - 0.014615 \cos(2B) - 0.04089 \sin(2B)) \]

\[ B = \frac{360(n - 1)}{365} \]

Equation 12 can be used to calculate the ratio of hourly diffuse irradiation \((I_d)\) to hourly global horizontal irradiation \((I)\); subtracting this value from one gives the ratio of hourly beam irradiation \((I_b)\) to hourly global horizontal irradiation. These relationships are derived using the hourly clearness index \((k_T)\), which is a function of hourly global horizontal irradiation and hourly extraterrestrial irradiation \((I_e)\), shown in Equation 13. Hourly extraterrestrial irradiation can be calculated using Equation 14, where the solar constant \((G_S)\) is equal to 1367 W/m².

\[ I_d = \begin{cases} 1.0 - 0.09k_T, & k_T \leq 0.22 \\ 0.9511 - 0.1604k_T + 4.388k_T^2 - 16.638k_T^3 + 12.336k_T^4, & 0.22 < k_T \leq 0.80 \\ 0.165, & k_T > 0.80 \end{cases} \]

\[ k_T = \frac{I}{I_o} \]

\[ I_o = G_S \left( \frac{12 \times 3600}{\pi} \right) \left( 1 + 0.033 \cos \left( \frac{360n}{366} \right) \right) \left( \cos(\varphi) \cos(\delta) \left( \sin(\omega_2) - \sin(\omega_1) \right) + \frac{\pi(\omega_2 - \omega_1)}{180} \sin(\varphi) \sin(\delta) \right) \]

Equation 15 shows the relationship between hourly beam irradiation, hourly diffuse irradiation and hourly global horizontal irradiation with hourly total irradiation received by the panel surface \((I_T)\), assuming the sky is isotropic. Reflectance in Equation 15 is attributed to ground reflectance \((\rho_g)\), which is equal to 0.2 for bare ground (Duffie & Beckman, 2013). The solar zenith angle \((\theta_2)\) can be calculated using Equation 6 by setting panel tilt and azimuth orientation to zero and solving for the incident angle, as shown in Equation 16. Once total irradiation is calculated on an hourly basis, the power output of each individual solar panel can be determined using Equation 3 and 4.

\[ I_T = I_b \left( \frac{\cos(\theta)}{\cos(\theta_2)} \right) + I_d \left( \frac{1 + \cos(\beta)}{2} \right) + I_p \rho_g \left( \frac{1 - \cos(\beta)}{2} \right) \]

\[ \cos(\theta_2) = \sin(\delta)\sin(\varphi) + \cos(\delta)\cos(\varphi)\cos(\omega) \]
### 4.2.4 Energy Storage

Adding energy storage to power systems with renewable energy components can offer many benefits, namely being able to smooth electricity produced and provide power consuming activities with a reliable source of electricity. For mining applications, having unpredictable power producing units such as wind turbines or PV solar panels may cause reliability issues for the mine’s power system. By adding energy storage, this risk can be mitigated to a certain extent by offering a buffer and help to maintain better scheduling of fossil fuel generators.

There are several energy storage options for hybrid renewable energy systems such as chemical batteries, fuel cells, compressed air, flywheels, as well as other newly developed technologies. Lithium-ion chemical batteries will be the focus of this case study, as they are widely used and proven to be reliable options. The technical operating parameters of Li-ion battery units used in this thesis are presented in Table 4.4. For confidentiality purposes, the supplier of these battery models will remain anonymous.

<table>
<thead>
<tr>
<th>Battery type</th>
<th>String Size (kWh)</th>
<th>Depth of Discharge (%)</th>
<th>Lifetime (cycles)</th>
<th>Round Trip Efficiency (%)</th>
<th>Operating Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lithium-ion</td>
<td>195</td>
<td>90%</td>
<td>6,000</td>
<td>87%</td>
<td>0 to 45</td>
</tr>
</tbody>
</table>

The capital cost for these battery units including transportation and installation is estimated to be C$900/kWh, which includes on-going operating costs over battery lifetime. The commissioning and engineering support for installation is expected to be C$250,000. Conventional battery management strategies employed in much of the available literature pertaining to HRES use batteries to balance load requirements with renewable energy based systems. However, this is not necessarily the case for the case study examined in this thesis, as fossil fuel generators will be sized to meet the entire power demand when necessary. Therefore, a different approach to battery management will be taken that targets smoothing renewable energy sources’ power output and manages sudden fluctuations.

Battery units are typically sized to maintain the installed power capacity of renewable energy power components for a duration of four hours. However, since the mine power system will be designed to be self-sufficient in case of lost production from renewable energy components, having four hours of back-up capacity is excessive. Therefore, instead of a four-hour charge and discharge period, this study will target a one-hour charge and discharge period. Although, if PV solar panels is the targeted renewable energy source, it may be advisable to extend the charge-discharge period to provide energy during hours of low solar radiation.

The battery sizing methodology used in this thesis will employ similar optimization techniques used as for sizing renewable energy components. The number of strings employed (\(N_{BAT}\)) will be varied incrementally to determine the optimal number that offers reliable power supply at minimal cost. Equation 17 will be used to calculate the installed capacity of battery units (\(E_{BAT}\)) in units of kWh (each string size is 195 kWh).

\[
E_{BAT} = N_{BAT} \times 195
\]

The following set of equations define the charging and discharging process for battery units. The primary role of battery units in this case study is to smooth power output from
renewable sources ($P_{\text{Renew}}$), which for the purposes of this thesis is defined using Equation 18. The state of charge (SOC) is a fundamental concept for batteries and a useful way to determine available discharge or storage capacity at each time interval. The SOC can range between a minimum SOC ($SOC_{\text{MIN}}$) to being fully charged, expressed numerically as one. The minimum SOC is a function of battery depth of discharge (DOD), as defined by manufacturer, and Equation 19 demonstrates this relationship. The SOC at each time interval is dependent on the SOC at the previous time interval, as well as the amount of energy stored or discharged from the battery units, shown using Equation 20.

$$P_{\text{Renew}}(t) = (N_{\text{WT}} \times P_{\text{WT}}(t)) + (N_{\text{PV}} \times P_{\text{PV}}(t))$$  

18

$$SOC_{\text{MIN}} = 1 - DOD$$  

19

$$SOC(t) = SOC(t - 1) + \frac{P_{\text{BAT}}(t)}{E_{\text{BAT}}}$$  

20

The hourly power output of battery units ($P_{\text{BAT}}$) is calculated as the difference between actual power output by renewable energy sources with the smoothed power, multiplied by the square root of round trip efficiency ($\eta$), as shown in Equation 22. The smoothed power output calculated using Equation 21 adjusts the power output supplied to the mine power system by considering the previous time step. This smoothing effect is meant to give operators time to moderate power produced by fossil fuel generators and better manage renewable energy power sources. The difference in power supplied to the power system in the previous time interval with the power produced in the current time interval is divided by a smoothing factor of eight. Furthermore, during the charging process, power supplied is limited by the smoothed power output calculated in Equation 21.

When the battery is charging $P_{\text{BAT}}$ will be positive and when the battery is discharging $P_{\text{BAT}}$ will be negative. Equations 23 and 24 are used to recalculate $P_{\text{BAT}}$ and power supplied by renewable energy sources during the charging process, while Equations 25 and 26 are used for the discharging process. This is done to ensure that there is enough storage and discharge capacity for these processes.

$$P_{\text{Renew}}(t) = P_{\text{Renew}}(t - 1) + \frac{P_{\text{Renew}}(t) - P_{\text{Renew}}(t - 1)}{8}$$  

21

$$P_{\text{BAT}}(t) = \left[(N_{\text{WT}} \times P_{\text{WT}}(t)) + (N_{\text{PV}} + P_{\text{PV}}(t)) - P_{\text{Renew}}(t)\right] \times \sqrt[8]{\eta}$$  

22

Charging process:

$$P_{\text{BAT}}(t) = \min(P_{\text{BAT}}(t), (1 - SOC(t - 1)) \times E_{\text{BAT}})$$  

23

$$P_{\text{Renew}}(t) = \min \left(P_{\text{Renew}}(t), \left(N_{\text{WT}} \times P_{\text{WT}}(t)\right) + \left(N_{\text{PV}} \times P_{\text{PV}}(t)\right) - P_{\text{BAT}}(t)\right)$$  

24

Discharging process:

$$P_{\text{BAT}}(t) = \max(P_{\text{BAT}}(t), -1 \times (SOC(t - 1) - SOC_{\text{MIN}}) \times E_{\text{BAT}})$$  

25

$$P_{\text{Renew}}(t) = \left(N_{\text{WT}} \times P_{\text{WT}}(t)\right) + \left(N_{\text{PV}} \times P_{\text{PV}}(t)\right) - P_{\text{BAT}}(t)$$  

26
4.2.5 Fossil Fuel Generators

The next components to be discussed are fossil fuel based generators in the form of diesel and dual fuel options. Diesel generators form the base case scenario for this study, while dual fuel generators offer an alternative power source, by running on up to 70% natural gas (Generac Power Systems, 2005). Dual fuel generators were selected over natural gas generators due to the expected fuel supply interruption, and can operate using 100% diesel fuel while natural gas is unavailable. Technical specifications will be described for each generator type and cost estimates will follow.

Fossil fuel generators are not weather dependent like renewable energy technologies, therefore, if properly maintained can provide reliable power when needed. Multiple generators acting in parallel make power capacity scalable, and in this case study, the number of generators will be sized to meet the expected connected load for the mine (10,614 kW). Therefore, if power output of wind turbines or PV solar panels fall, the fossil fuel generators will be able to make up for reduced power output. Generators can operate at various levels, in theory ranging from 0% to 110% of rated power capacity. However, to promote longevity, a more practical operating range is from 50% to 90%. This operating range will be used in subsequent analysis, where the number of generators operating hourly will operate at 90% when possible, and no less than 50%.

Generators can be used for multiple purposes: standby, continuous and prime power generation. Standby power generation describes generators that can achieve up to 100% power generation in emergency situations and can be used as such for the duration of power shortage. Unlike standby operation, continuous generation as the name implies, allows generators to operate as a primary power source at relatively fixed power output during operation. Therefore, can be used to provide baseload power, however are unable to handle varying electrical loads. The final configuration, prime power generation, is suitable for supplying power to varying loads, and therefore is better suited for dynamic power demand. Generators are offered in a range of sizes, from small backup systems for homeowners to large systems for industrial scale applications. The latter case applies to mining projects, where mine power demand rivals that of small towns, therefore from an economic standpoint, generators with large power capacities are used.

Generac 2,000 kW diesel generator has been selected for the diesel aspect of this case study, as Generac is a widely used generator manufacturer and this model is the largest size offered. The Generac 2,000 kW diesel generator has a standby and prime power rating of 2,000 kW and 1,800 kW, respectively. Fuel consumption rates are provided at four load percent values: 25%, 50%, 75% and 100% on generator data sheet. A linear trendline will be used to depict the fuel consumption curve at different loads, as seen in Figure 4.10 for prime power generation. The prime power rating will be treated as the generator installed capacity ($Pr_{Gen}$) for this study, since generators are the primary means of power supply and need to be equipped to handle varying power demand.
Fuel Consumption Curve for 1,800 kW (Prime) Diesel Generator

\[ y = 0.2873x + 24.2 \]

Figure 4.10 Fuel consumption curve for Generac 1,800 kW (prime) diesel generator

The all-in capital cost estimation for this generator model is C$700,000, which includes transport and installation. The operating cost per generator is estimated to be C$0.009/kWh. The Company estimates that the expected diesel fuel price for power generation at the case study site including transportation costs is C$0.896/L. However, as with the price of commodities and other natural resources this could change up to and during the project lifetime. In addition to the cost of generators, diesel fuel needs to be stored on site for continuous power generation. The capital cost estimation of diesel storage tanks is C$0.20/L of total fuel capacity, and a duration of five weeks will be used to define the required diesel fuel storage capacity for this case study.

The second generator option to be explored in this case study is a dual fuel generator, capable of running on diesel only and a combination of diesel and natural gas. This option has been selected over natural gas dedicated generators due to the fuel interruption risk at the case study location. While road access and regular fuel delivery is available, the dual fuel generators will use a combination of natural gas and diesel fuel. Generac offers dual fuel generator options in the form of dedicated generators, and dual fuel kits which can be used with certain diesel generator models. The dual fuel generators offered by Generac are available in two sizes: 600 kW and 500 kW, and are only recommended for standby operation. Therefore, the InteliBifuel kit manufactured by ComAp will be targeted for this case study. It is recommended that kits be installed at factory to ensure reliable operation. The expected added capital cost of dual fuel kits is C$100,000 per generator and there are no expected additional operating costs for dual fuel operation, although minor service parts may need replacement over the generator life. Fuel consumption curves supplied by ComAp will be used in subsequent analysis, however this information is considered as confidential and has therefore been excluded from this thesis.

The operating cost of this generator is assumed to be the same as for the diesel generator (C$0.009/kWh). The cost of diesel fuel will remain the same (C$0.896/L), while the expected cost of natural gas at the case study site is C$20.34/GJ. The dual fuel generators use natural gas, however, liquefied natural gas (LNG) is delivered to site. Therefore, storage and vaporization units are required to convert this into a useable product, and the estimated capital cost of such units is C$1.7 million. The natural gas storage capacity associated with this estimate is assumed to sustain one week of dual fuel operation.
The number of generators required ($N_{Gen}$) can be calculated using Equation 27, where the number of generators is dependent on the expected connected electrical load ($P_{CL}$), as well as rated power capacity of individual generator ($P_{R,Gen}$). Two additional units should be added to account for maintenance and unexpected generator failure. As discussed in Section 4.2.1, the expected connected load used in this study equal to 10,614 kW. The rated power capacity of each generator model is 1,800 kW under prime operating conditions. Therefore, the number of generators (diesel or dual fuel) required is eight.

$$N_{Gen} = \text{roundup} \left( \frac{P_{CL}}{P_{R,Gen}} \right) + 2$$

The hourly power generation required from fossil fuel generators will vary over the course of the sample year depending on wind speed, ambient temperature and solar radiation. Equation 28 demonstrates this relationship where the power required by generators ($P_{Gen}$) is the difference between hourly power demand ($P_L$) and power produced by renewable energy components. The annual electricity produced by generators ($AEP_{Gen}$) is calculated using Equation 29.

$$P_{gen}(t) = P_L - P_{\text{Renew}}(t)$$

$$AEP_{Gen} = \sum_{t=1}^{8784} P_{gen}(t)$$

### 4.2.6 Summary

This section is meant to briefly summarize the design and cost assumptions made in the previous sections for each power system component. Table 4.5 summarizes the rated power capacity on a per unit basis, and number of units to be investigated for this case study. Both PV solar panels and Li-ion batteries do not have a predefined maximum number of units. This is due to available space not being a significant constraint for these technologies and it is expected that the cost of these systems will inhibit large scale deployment.

<table>
<thead>
<tr>
<th>Energy Source</th>
<th>Model</th>
<th>Rated Power (kW$^2$)</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesel Generator</td>
<td>Generac IDLC2000</td>
<td>1,800</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>Dual Fuel Kit</td>
<td>ComAp InteliBifuel</td>
<td>$^3$</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>Wind Turbine</td>
<td>EWT DW61-1.0 MW</td>
<td>1,000</td>
<td>0</td>
<td>7</td>
</tr>
<tr>
<td>PV Solar Panel</td>
<td>REC TwinPeak 2S 72</td>
<td>0.35</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>Li-Ion Battery</td>
<td>n/a$^4$</td>
<td>195 (kWh)</td>
<td>0</td>
<td>-</td>
</tr>
</tbody>
</table>

The following Table 4.6 outlines the capital cost, operating cost and fuel cost assumptions for each power system component. Values are expressed on a per unit basis unless otherwise specified. In addition to these values, annual electricity consumption of 68,620,000 kWh will be used to simulate a sample year consisting of 8784 hours. Hourly

$^2$ Rated power specified on a per unit basis
$^3$ Dual fuel kit assumes same rated power as diesel generator
$^4$ Battery provider will remain anonymous in this thesis
power demand will be assumed constant and equal to 7,812 kW over the nine year mine life.

Table 4.6 Summary of economic assumptions for power system components per unit

<table>
<thead>
<tr>
<th>Energy Source</th>
<th>Capital Cost (CS)</th>
<th>Annual Operating Cost (CS)</th>
<th>Fuel Cost (CS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesel Generator</td>
<td>700,000</td>
<td>0.009/kWh</td>
<td>0.896/L(^5)</td>
</tr>
<tr>
<td>Dual Fuel Generator</td>
<td>800,000</td>
<td>0.009/kWh</td>
<td>20.34/GJ(^6)</td>
</tr>
<tr>
<td>Wind Turbine</td>
<td>2,000,000</td>
<td>40,000/turbine</td>
<td>-</td>
</tr>
<tr>
<td>PV Solar Panel</td>
<td>2.7/W</td>
<td>10/kW</td>
<td>-</td>
</tr>
<tr>
<td>Li-Ion Battery</td>
<td>900/kWh</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

4.3 Levelized Cost of Energy

There are several methods to compare energy projects and technologies by their respective costs, such as net present cost, internal rate of return and payback period. However, the methods listed here do not provide a complete picture as there is no inclusion of energy output. Therefore, a better metric to make comparisons is the cost of energy, which is typically defined by a unit of currency per unit of energy output (CS/kWh). Furthermore, the levelized cost of energy (LCOE) considers the total life-cycle cost (TLCC) of an energy system and the total amount of energy generated, both of which are discounted over the project’s operating lifetime. This allows projects of different scales, time periods and technologies to be more readily compared.

The equation used in this thesis to calculate LCOE is presented in Equation 30, where the energy output in year \( n \) is defined as \( Q_n \), and the present value of TLCC is defined using Equation 31 (Short, Packey, & Holt, 1995). The discount rate \((d)\) used in this study is 10%, which accounts for the risk perception associated with remote power generation and renewables (Oxera, 2011). The analysis period \((N)\) used for economic analysis is equal to the mine life of nine years. It is expected that energy output will be different for each energy technology and be dependent on climatic conditions and load requirements. The cost of the power system in each year \((TC_n)\) is also a function of energy technology, and as described in Equation 32, is the sum of capital cost \((C_n)\), operating cost \((O_n)\) and fuel cost \((F_n)\) incurred each year.

\[
LCOE = \frac{TLCC}{\sum_{n=1}^{N} \frac{Q_n}{(1+d)^n}} \tag{30}
\]

\[
TLCC = \sum_{n=0}^{N} \frac{TC_n}{(1+d)^n} \tag{31}
\]

\[
TC_n = C_n + O_n + F_n \tag{32}
\]

In addition to LCOE, net present cost (NPC), net present value (NPV), internal rate of return (IRR), and simple payback period will be used to compare system configurations.

\(^5\) Diesel fuel price

\(^6\) Natural gas price
NPC is calculated in a similar manner as TLCC, as seen in Equation 31. By subtracting two cash flows (base case and alternative scenario expressed as \( TC_{\text{Base case}} \) and \( TC_{\text{Alternative}} \), respectively), the NPV of each alternative scenario can be calculated using Equation 33 (Short, Packey, & Holt, 1995). Furthermore, IRR is the rate at which NPV for the differenced cashflows is equal to zero, as shown in Equation 34. Lastly, simple payback period is a method of calculating the length of time it will take for the system with higher up-front capital costs to become more profitable than the alternative option. Equation 35 illustrates this relationship between two options, where the difference in initial capital cost is divided by the incremental annual savings to determine the payback time (Tester, et al, 2012).

\[
NPV = \sum_{n=0}^{N} \frac{TC_{\text{Base case},n} - TC_{\text{Alternative},n}}{(1 + d)^n}
\]

\[
0 = \sum_{n=0}^{N} \frac{TC_{\text{Base case},n} - TC_{\text{Alternative},n}}{(1 + IRR)^n}
\]

\[
\text{Payback time, years} = \frac{\text{initial capital cost, } \$}{\text{incremental annual savings, } \$/\text{year}}
\]

### 4.4 Greenhouse Gas Emissions

When considering different energy sources, greenhouse gas emission rates should be included in comparative analyses to reflect environmental impacts. There are two primary ways to convey this information, by means of carbon dioxide (CO\(_2\)) and carbon dioxide equivalent (CO\(_2\)e) emission rates. As the name implies CO\(_2\) emission rates refer only to CO\(_2\) emitted, however, combustion of fossil fuels and other GHG producing sources emit other gaseous compounds as well. Whereas, CO\(_2\)e reflects all greenhouse gases emitted, by applying a weighting factor for each GHG based on their respective global warming potential and presents the environmental impact in a CO\(_2\) equivalent. Furthermore, carbon pricing policies already implemented in Canada (for example: British Columbia, Alberta, Ontario and Quebec) adhere to CO\(_2\)e. Therefore, CO\(_2\)e emission rates will be used in this thesis to reflect the environmental impact of energy options.

A further consideration for GHG emissions, is if to analyze emissions produced during the entire life cycle of an energy technology (i.e. mineral and metal extraction and refinement, material manufacturing, transportation, operation, decommissioning and material disposal), or to only consider emissions produced during power generation. Although estimates of life cycle emission rates are available, there is substantial variability and uncertainty involved in this calculation. For example, extraction and processing of materials and fuel is location dependent and rarely uniform on a global scale. Furthermore, it is difficult to accurately track an energy technology on its journey from ‘cradle to grave’. Therefore, although it is important to acknowledge that no energy technology is truly carbon neutral for the reasons listed above, this thesis will simplify its methods to consider only point source emissions during power generation. A table of values of GHG emission rates used in this study are presented in Table 4.7, where the GHG emission rates during operation for wind energy, solar energy and energy storage will be assumed to be null.
Table 4.7 GHG emission factors for stationary combustion of fossil fuels (British Columbia Ministry of Environment, 2016)

<table>
<thead>
<tr>
<th>Fuel Type</th>
<th>Energy Conversion Factor</th>
<th>CO₂</th>
<th>CO₂e</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesel Fuel</td>
<td>0.03830 GJ/L</td>
<td>67.43</td>
<td>70.62</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>0.03885 GJ/m³</td>
<td>49.58</td>
<td>49.87</td>
</tr>
</tbody>
</table>

4.5 Scenario Evaluation

Of the seven scenarios to be evaluated, calculation based evaluation will be suitable for the first two (diesel generator only and dual fuel generator only), while an iterative optimization approach will be used to determine the optimal number of renewable energy components in the remaining scenarios (dual fuel/wind, dual fuel/solar, dual fuel/wind/battery, dual fuel/solar/battery and dual fuel/wind/solar/battery). In the first two scenarios, the number of generators selected will be exclusively a function of power demand, and using Equation 27 has been calculated to be eight. Using the equations and fuel consumption rates presented in the previous sections, the following metrics will be calculated:

- Diesel consumption
- Natural gas consumption
- CO₂e emissions
- Capital cost
- Annual operating cost
- NPC
- LCOE

An iterative approach will be taken to determine the optimal number of renewable energy components for the remaining configurations. The number of wind turbines, PV solar panels and battery units will be varied systematically so that all possible combinations will be evaluated. The configuration with the lowest LCOE will be considered as the most desirable option. Figure 4.11 illustrates the methodology taken for the iterative optimization method, where MATLAB is used for simulation and evaluation. In addition to the metrics listed above, the number of renewable energy components used (including battery units), as well as energy output is saved for each simulation.
Figure 4.11 Flowchart outlining the methodology employed to carry out iterative optimization


4.6 Validation Method

It is valuable to compare results of the scenario analysis described previously, to ensure that the findings are reliable. An alternative method to modeling the scenarios is to use commercially available design software. HOMER Pro is a microgrid design software that can be used for this purpose, as it models and optimizes hybrid renewable energy systems for grid connected or standalone applications. Many researches appear to be using HOMER, and its use in industry is growing. This design software uses its own methods and data sources to calculate power output and to size the desired power system, although users can import their own resource data. Using HOMER to validate this study’s results should provide insight into the quality of findings obtained from this thesis. The user interface guides the user through the following steps:

1. Choose location
2. Add power demand and load profile
3. Select components (wind turbine, PV solar panel, generator, etc.)
4. Select or import resource data
5. Input project parameters (lifetime, inflation, emission penalties, etc.)
6. Run HOMER
7. Obtain list of results and sensitivity analysis

The depth of analysis that HOMER offers is extensive, and the user can tailor its complexity to their preference. For the purposes of this thesis, the assumptions made pertaining to type and rated power capacity of energy components as well as cost information will be used as inputs in HOMER. Furthermore, the same load profile and resource data will be imported and used in the analysis. Dual fuel generators are not an available option for use in HOMER. Therefore, the scenarios will be evaluated in MATLAB and HOMER using diesel generators for validation purposes and exclude the dual fuel generator only scenario. A comparison between MATLAB derived results and those calculated using HOMER will be presented in Section 5.2.

4.7 Sensitivity Analysis

The purpose of including a sensitivity analysis in this thesis is to assess the impact that scenario inputs and assumptions have on final results. In other words, due to uncertainty of project assumptions, be it resource data or cost information, it is sensible to evaluate the effect that changes in key inputs have on the recommended HRES configuration and system cost. Key inputs that will be subject to a sensitivity analysis are summarized as follows:

- Capital cost of generators and renewable energy components
- Cost of fuel (both diesel and natural gas)
- Hourly renewable energy resource data
- Mine life
- Carbon tax

Due to the reliance on preliminary estimation of capital costs, in addition to the project being remotely located, it is important to assess the impact that increased costs have on the final results. Capital cost and fuel price estimates used in this thesis will be varied from 50%
to 150%, in 10% intervals. Although a certain degree of confidence is upheld by meteorological data used for this case study, it is common for meteorological conditions to fluctuate yearly. Therefore, the hourly meteorological data will also be varied from 50% to 150%, in 10% intervals. Furthermore, mining operations often extend their mine life once operation commences, as ongoing exploration activities may identify a larger or higher quality orebody than expected. For this reason, the operating lifetime used in this study will increase from 9 to 15, in one-year intervals.

In October 2016, the Canadian Government announced that provinces and territories must have carbon pricing in place by 2018 (Government of Canada, 2016). The carbon pricing mechanism can be unique for each jurisdiction and may consist of a carbon tax or emission trading scheme. If no carbon pricing mechanism is established by this time, the Canadian government will impose a carbon tax starting at C$10/tonne, rising by C$10 each year until 2022 when it reaches C$50/tonne. Any alternative carbon pricing mechanism must have equivalent or greater value than the standard set by the Government of Canada. As the January 1, 2018 deadline has passed, the Canadian Government has proposed a timeline for those jurisdictions not yet in compliance, which includes the Yukon territory. Whether provincial and territorial governments choose to adopt the federal carbon pricing mechanism or if they intend to implement their own, it is expected that an equivalent C$10/tonne carbon price be implemented by fall 2018. The anticipated start date for the case study’s prospective mining operation is near 2022. Therefore, a carbon tax of C$50/tonne will be applied to the price of diesel and natural gas using emission rates outlined in Table 4.7, and the results will be included in the sensitivity analysis.
Chapter 5

Results

This chapter focuses on presenting the results obtained by carrying out the methodology outlined in the previous chapter. The aim of this thesis is to determine the optimal configuration of power system components for a remote mining operation in the Yukon territory, given local renewable energy resource data, mining assumptions and technical constraints. The LCOE is assumed to be the defining metric in determining the recommended configuration. While other factors such as GHG emissions, initial capital cost, annual savings, payback period, NPV and IRR are also considered. The following sections summarize findings from the scenario analysis, validation using HOMER, sensitivity analysis and carbon tax implications.

5.1 Scenario Analysis

The proceeding scenario analysis is intended to present findings for various power system configurations, where diesel generators are used as a base case and alternative scenarios using renewable energy sources and dual fuel generators (diesel and natural gas) are analyzed. The LCOE of using strictly wind or solar energy as calculated for this case study is C$0.266/kWh and C$0.470/kWh, respectively. Since the LCOE of solar energy is considerably greater than the base case diesel generator scenario (C$0.295/kWh), it was not included as a viable option. Furthermore, scenarios where wind turbines are used without battery units have also been excluded from further analysis. This is due to the operational difficulty these scenarios pose as they have no means to control renewable energy power output. Figure 5.3 illustrates the effects of wind turbine power output with and without battery units. Therefore, only three scenarios remain of the previously identified options, and are as follows:

- Diesel generators (base case)
- Dual fuel generators
- Dual fuel generators, wind turbines and battery storage

Table 5.1 and Table 5.2 present the results for energy technology components used in these scenarios, with the first table stating rated power capacity and second specifying average power output. The lower power output of wind turbines with respect to rated power is due to the low wind speeds experienced at the case study location. Table 5.3 presents the fuel consumption and economic results as calculated for each scenario. As a reminder to the reader, NPC, LCOE and NPV were calculated using a 10% discount rate over nine years, while simple payback period is undiscounted.
Table 5.1 Scenario analysis results: Rated power capacity of energy technologies

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Diesel</th>
<th>Dual Fuel</th>
<th>Dual Fuel/ Wind/ Battery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind Turbines (MW)</td>
<td>0</td>
<td>0</td>
<td>7</td>
</tr>
<tr>
<td>Batteries (MWh)</td>
<td>0</td>
<td>0</td>
<td>0.6</td>
</tr>
<tr>
<td>Diesel Generators (MW)</td>
<td>14.4</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Dual Fuel Generators (MW)</td>
<td>0</td>
<td>14.4</td>
<td>14.4</td>
</tr>
</tbody>
</table>

Table 5.2 Scenario analysis results: Average power output of energy technologies

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Diesel</th>
<th>Dual Fuel</th>
<th>Dual Fuel/ Wind/ Battery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind Turbines (MW)</td>
<td>0</td>
<td>0</td>
<td>0.8</td>
</tr>
<tr>
<td>Batteries (MW)</td>
<td>0</td>
<td>0</td>
<td>0.04</td>
</tr>
<tr>
<td>Diesel Generators (MW)</td>
<td>7.8</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Dual Fuel Generators (MW)</td>
<td>0</td>
<td>7.8</td>
<td>7.0</td>
</tr>
</tbody>
</table>

Table 5.3 Scenario analysis results: Fuel consumption and economic summary

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Diesel</th>
<th>Dual Fuel</th>
<th>Dual Fuel/ Wind/ Battery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual Diesel (Million L)</td>
<td>20.8</td>
<td>10.8</td>
<td>9.8</td>
</tr>
<tr>
<td>Annual Natural Gas (Million GJ)</td>
<td>0</td>
<td>0.42</td>
<td>0.38</td>
</tr>
<tr>
<td>Annual CO₂e (Tonnes)</td>
<td>56,200</td>
<td>50,400</td>
<td>45,400</td>
</tr>
<tr>
<td>Capital Cost (CS Million)</td>
<td>6.0</td>
<td>8.5</td>
<td>23.3</td>
</tr>
<tr>
<td>Annual Operating Cost (CS Million)</td>
<td>19.2</td>
<td>18.9</td>
<td>17.3</td>
</tr>
<tr>
<td>NPC (CS Million)</td>
<td>116.8</td>
<td>117.5</td>
<td>123.1</td>
</tr>
<tr>
<td><strong>LCOE (CS/kWh)</strong></td>
<td><strong>0.295</strong></td>
<td><strong>0.297</strong></td>
<td><strong>0.312</strong></td>
</tr>
<tr>
<td>Annual Savings (CS Million)</td>
<td>-</td>
<td>0.3</td>
<td>1.9</td>
</tr>
<tr>
<td>Simple Payback (Years)</td>
<td>-</td>
<td>8.2</td>
<td>9.1</td>
</tr>
<tr>
<td>NPV (CS Million)</td>
<td>-</td>
<td>-0.8</td>
<td>-6.4</td>
</tr>
<tr>
<td>IRR (%)</td>
<td>-</td>
<td>1.9</td>
<td>-</td>
</tr>
</tbody>
</table>
It is evident from Table 5.3 that under current market conditions and assumptions made, diesel generators yield the lowest LCOE with respect to the other scenarios. However, dual fuel generators offer a comparable cost while halving diesel fuel consumption and emitting approximately 6,000 fewer tonnes of CO₂e, both on an annual basis. The dual fuel/wind/battery scenario results in a slightly higher LCOE and provides approximately 10% of the mine’s electricity demand. This scenario produces approximately 10,000 fewer tonnes of CO₂e annually than the diesel generator scenario and offers close to C$2 million in annual savings, due to lower operating costs. The simple payback periods for dual fuel and dual fuel/wind/battery are 8.2 and 9.1 years, respectively.

The next series of graphs illustrate the optimization process for wind turbines and battery units. The optimization process for wind turbines is shown in Figure 5.1, where the number of wind turbines yielding the lowest LCOE is nine, however the maximum number of wind turbines that can be used is seven, due to spacing requirements and available area. Therefore, seven wind turbines were selected as the optimal number for this case study. Increasing the number of wind turbines past nine results in a higher LCOE. This is due to the power generated by wind turbines beginning to exceed the hourly power demand, and subsequently, some power is discarded. Therefore, when the number of wind turbines is greater than nine, uniformly increasing the cost does not correspond to a uniform increase in energy output, and LCOE gets higher.

![Wind Turbine Optimization](image_url)

**Figure 5.1** Number of wind turbine optimization for dual fuel/wind scenario

Figure 5.2 presents the optimization process for battery units, where the number of wind turbines is maintained at seven (optimum number of wind turbines), while the number of battery strings are increased incrementally. In this case, the LCOE is minimized using three battery strings (585 kWh). Increasing the number of battery strings increases the useable amount of power generated from wind turbines, however LCOE continues to increase due to added capital costs.
Figure 5.2 Number of battery unit optimization for dual fuel/wind/battery scenario utilizing seven wind turbines

Figure 5.3 demonstrates the effect of “smoothed” power output produced by the battery units for the dual fuel/wind/battery scenario. A random seven-day analysis period was selected and Figure 5.3 presents the results beginning on May 6 at 12:00 a.m. of the sample year. The damping effect is more evident in this figure since short term fluctuations are flattened and sharp increases in power generated by wind turbines is gradually reached. However, some power produced by wind turbines is discarded when wind speeds increase suddenly, and batteries are fully charged. Approximately 3.2 GWh of electricity per year is lost due to battery smoothing, which is equivalent to 32% of total energy output by wind turbines. Sharp decreases of power output by wind turbines on the other hand cannot be entirely smoothed using battery units. However, it is anticipated that enough energy is stored to provide operators time to adapt to changes in the wind regime and schedule generators accordingly. The hourly battery state of charge (SOC) is also presented in this figure and on average 1.5 round trip cycles are made per day. Given a battery lifetime of 6,000 cycles, these battery units can operate for approximately 10 years before needing to be replaced.
Figure 5.3 Smoothed power output vs power generated by wind turbines for dual fuel/wind/battery scenario

5.2 Validation

The next section of this chapter deals with validating the results obtained by modeling and evaluating each scenario using MATLAB, and HOMER was used for this purpose. As discussed previously, inputs used in HOMER for validation closely resemble the conditions and components used in the scenario analysis. A detailed summary of project assumptions and component parameters is listed in Appendix B and resource data used in MATLAB was imported into the software. One key limitation when using HOMER is that dual fuel generators are not an available option. Therefore, validation was carried out for each scenario using diesel generators, and results obtained using MATLAB were amended to use diesel generators in each scenario. The validation results for annual diesel fuel consumption and wind turbine power output, with and without battery units is presented in Table 5.4. The main difference in these results is the annual wind energy output with batteries. This is due to HOMER not accounting for battery smoothing effects and lost energy production, due to quickly changing wind speeds. Whereas, the battery power output methodology employed in this study discards energy when batteries are fully charged, and wind speed suddenly increase.

Table 5.4 HOMER validation results for annual fuel consumption and wind energy output

<table>
<thead>
<tr>
<th></th>
<th>Diesel Fuel (Million L)</th>
<th>Wind Energy (kWh)</th>
<th>Wind Energy with Batteries (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Results</td>
<td>20.8</td>
<td>10,155,850</td>
<td>6,930,681</td>
</tr>
<tr>
<td>HOMER</td>
<td>20.7</td>
<td>10,199,614</td>
<td>10,199,614</td>
</tr>
<tr>
<td>Difference</td>
<td>-0.4%</td>
<td>0.4%</td>
<td>47%</td>
</tr>
</tbody>
</table>
The LCOE values obtained using HOMER for diesel, wind, and solar energy closely match those calculated in this study, as shown in Figure 5.4. A greater LCOE discrepancy exists for the diesel/wind/battery scenario, as HOMER assumes that all energy produced by wind turbines can be used, which is not the assumption made in this thesis. Furthermore, the average wind speed and solar radiation from comparable case study locations are 5.4 m/s and 113 W/m², according to HOMER sources. These values are slightly higher than those used in this study, however validation was carried out using the datasets provided by weather station and AWS Truepower.

![LCOE Validation Using HOMER Pro](image)

**Figure 5.4** HOMER LCOE validation results for energy technologies evaluated in this study

### 5.3 Sensitivity Analysis

A sensitivity analysis was performed on several of this case study’s key inputs to analyze their respective impacts on project economics. Doing so will account for uncertainty in estimations and identify aspects that require greater delineation. The focus of this sensitivity analysis will be the dual fuel/wind/battery scenario, as this scenario captures the effect that capital costs and fuel prices have on LCOE in the other scenarios. The effect of mine life will be analyzed for the diesel, dual fuel and dual fuel/wind/battery scenario.

Figure 5.5 presents the sensitivity analysis of capital cost estimates for the dual fuel/wind/battery scenario. It appears that LCOE is most sensitive to changes in wind turbine capital cost, followed by the capital cost estimates of dual fuel generators and battery units. This is due to the capital cost of wind turbines (CS$14 million) constituting a large fraction of the total capital cost for this scenario (CS$23.3 million), and therefore is the most sensitive capital cost component. The effect that generator capital cost estimates have on the LCOE for diesel and dual fuel scenarios is similar to the dual fuel generator sensitivity presented in Figure 5.5.
Figure 5.5 Capital cost sensitivity analysis for dual fuel/wind/battery scenario

The effect that varying fuel prices and wind speeds have on LCOE for the dual fuel/wind/battery scenario is presented in Figure 5.6. The price of diesel and natural gas are independently and mutually varied, while wind speed is also varied by the same factors. In this figure, it appears that LCOE is highly sensitive to changes in both fuel prices, followed by changes in one fuel price while the other stays constant. In comparison to the other variables analyzed in this sensitivity analysis, fuel prices are the most influential parameter on LCOE for all scenarios evaluated. The diesel generator scenario experiences a similar diesel fuel price sensitivity as both fuels have in Figure 5.6. Dual fuel generators provide more stable conditions for changes in only one fuel price, and the fuel price sensitivities of this scenario are similar to those presented in Figure 5.6. The effect of wind speed on LCOE for the dual fuel/wind/battery scenario is greater than for capital cost estimates, however less than fuel prices.

Figure 5.6 Fuel price and wind speed sensitivity analysis for dual fuel/wind/battery scenario
Figure 5.7 illustrates the effect of wind speed and diesel fuel price on the resulting IRR for the dual fuel/wind/battery scenario compared to diesel generators. This figure was created by varying the inputs in MATLAB to determine a new IRR for average wind speeds ranging from 0 m/s to 10 m/s, and diesel fuel prices from C$0/L to C$2/L. Under the current diesel fuel price assumption used in this case study (C$0.896/L), the average wind speed required to make this scenario economically favorable to diesel generators (IRR > 10%) is approximately 6 m/s. Furthermore, by maintaining the average wind speed at 5.2 m/s, the diesel fuel price would need to exceed C$1/L for an IRR greater than 10%.

![Figure 5.7 IRR sensitivity analysis for wind speed and diesel fuel price for dual fuel/wind/battery scenario](image)

Figure 5.8 presents the results of extended mine life analysis, where the mine life is increased from 9 to 15 in one-year increments. LCOE is evaluated for the following scenarios: diesel, dual fuel and dual fuel/wind/battery. This analysis assumes that power demand in each year remains the same, and battery unit capital cost reoccurs in year 10 for the dual fuel/wind/battery scenario. The LCOE of the diesel and dual fuel scenarios remains relatively flat over the analysis horizon, however the dual fuel/wind/battery scenario provides improving economics as the mine life is extended.

Upon performing sensitivity analyses on several key parameters, the LCOE for the dual fuel/wind/battery scenario appears to be resilient to changes in the capital cost of generators and battery units. Although LCOE is more sensitive to the capital cost of wind turbines, as seen in Figure 5.5, the fuel price and wind speed parameters presented in Figure 5.6 have a greater impact on LCOE for this scenario. Of all the parameters analyzed, fuel prices pose the greatest variability to LCOE for each scenario.
5.4 Carbon Tax

The following analyses was conducted under the assumption that a C$50/tonne carbon tax is imposed by the Government of Canada on Canadian provinces and territories. The carbon tax is augmented to the price of fossil fuels, yielding diesel fuel and natural gas prices of C$1.03/L and C$22.83/GJ, respectively. Table 5.5 presents the effect of a C$50/tonne carbon tax on the scenario analysis results. Given that all scenarios are largely dependent on fossil fuels, the LCOE of each scenario increases on average by C$0.035. However, the difference in LCOE with and without a carbon tax is lower for all scenarios compared to the diesel generator base case. The dual fuel scenario now becomes the most economic option, having a simple payback period of 4.2 years and IRR of 19%, with respect to the base case. The simple payback period of dual fuel/wind/battery is 7.1 years, however the NPV of this scenario with respect to the base case remains negative.
Table 5.5 Scenario analysis results with carbon tax: Fuel consumption and economic summary

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Diesel (Million L)</th>
<th>Dual Fuel (Million GJ)</th>
<th>Dual Fuel/ Wind/ Battery (CS Million)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual Diesel</td>
<td>20.8</td>
<td>10.8</td>
<td>9.7</td>
</tr>
<tr>
<td>Annual Natural Gas</td>
<td>0</td>
<td>0.42</td>
<td>0.38</td>
</tr>
<tr>
<td>Annual CO₂e</td>
<td>56,200</td>
<td>50,400</td>
<td>45,200</td>
</tr>
<tr>
<td>Capital Cost</td>
<td>6.0</td>
<td>8.5</td>
<td>23.8</td>
</tr>
<tr>
<td>Annual Operating Cost</td>
<td>22.0</td>
<td>21.4</td>
<td>19.5</td>
</tr>
<tr>
<td>NPC</td>
<td>132.9</td>
<td>132.0</td>
<td>136.2</td>
</tr>
<tr>
<td>LCOE (CS/kWh)</td>
<td>0.336</td>
<td>0.334</td>
<td>0.345</td>
</tr>
<tr>
<td>Annual Savings</td>
<td>-</td>
<td>0.6</td>
<td>2.4</td>
</tr>
<tr>
<td>Simple Payback</td>
<td>-</td>
<td>4.2</td>
<td>7.1</td>
</tr>
<tr>
<td>NPV</td>
<td>-</td>
<td>0.9</td>
<td>-3.3</td>
</tr>
<tr>
<td>IRR (%)</td>
<td>-</td>
<td>18.6</td>
<td>5.0</td>
</tr>
</tbody>
</table>

An IRR sensitivity plot is presented in Figure 5.9, showing the effects of wind speed and carbon tax prices on IRR for the dual fuel/wind/battery scenario with respect to diesel generators. It is apparent that for this scenario to become economically feasible (IRR > 10%), the carbon tax needs to reach or exceed CS$100/tonne. The expected 2022 carbon tax price (CS$50/tonne) yields an IRR of roughly 5%.

![Figure 5.9 IRR sensitivity analysis for wind speed and carbon tax price for dual fuel/wind/battery scenario](image)
To briefly summarize the main findings from this chapter, diesel and dual fuel generator scenarios offer the lowest LCOE with respect to the alternative options. Use of dual fuel generators decreases annual diesel fuel consumption by half and CO$_2$e emissions by 6,000 tonnes annually. Solar energy is not a viable option for this case study location, however wind energy used with dual fuel generators and batteries is close to being competitive with the diesel and dual fuel generator scenarios. Although this scenario is more capital intensive, annual savings of C$2 million are achievable, in addition to approximately 10,000 fewer tonnes of CO$_2$e emitted annually. Upon conducting an IRR sensitivity to average wind speed and diesel fuel price, the dual fuel/wind/battery scenario would need to experience 6 m/s average wind speed or at minimum C$1/L diesel fuel price for the IRR of this scenario to exceed 10%.

Validating scenario analysis results using HOMER provided little discrepancy, where the greatest difference results from different battery power output methodologies. The sensitivity analysis identified fuel prices as having the greatest impact on LCOE for all scenarios and wind speed has a similar impact to LCOE for the dual fuel/wind/battery scenario. The effect of a C$50/tonne carbon tax was also analyzed, and as a result, the LCOE for each scenario increased by on average C$0.035. Under these conditions, dual fuel generators appear to be economically favorable to diesel generators. For the dual fuel/wind/battery scenario to provide better economics than the diesel generator scenario, the carbon tax would need to reach approximately C$100/tonne.
Chapter 6

Discussion

The previous chapters of this thesis have covered several topics, including an introduction to the case study, reviewing literature pertaining to mine power systems, hybrid renewable energy systems and similar techno-economic studies, as well as outlining the selected methodology to carry out the objectives of this thesis. The previous chapter summarized the case study results, where multiple power system configurations were evaluated for the given location and load requirement. The assessed scenarios included a base case (diesel generators) and alternative energy options in the form of dual fuel generators, wind turbines, PV solar panels and Li-ion batteries. The purpose of performing this analysis was to determine the technical and economic potential of using alternative energy sources for power generation at remote mining operations, using a case study in the Yukon territory as an example. The aim of an alternative power system is to reduce consumption of imported diesel fuel, thereby lowering operating costs and GHG emissions.

Under current market prices and renewable energy resource conditions at the case study location, it was determined that diesel generators offer the lowest LCOE of the scenarios evaluated (C$0.295/kWh). The capital cost and annual operating cost of this scenario are C$6 million and C$19.2 million, respectively. Natural gas generators were targeted as an alternative power source to diesel generators, given lower fuel costs and associated GHG emissions. However, a fuel supply interruption is expected at the case study location making lengthy natural gas storage an expensive and risky endeavor. Therefore, dual fuel generators were selected as a suitable alternative given their ability to use a mix of natural gas and diesel while natural gas is available, and 100% diesel when fuel supply is interrupted. The LCOE of dual fuel generators is C$0.297/kWh. The capital cost of this scenario is estimated to be C$8.5 million, with an annual operating cost of C$18.9 million. The simple payback period for this scenario with respect to the base case is 8.2 years with annual CO₂e emission savings of approximately 6,000 tonnes.

Investigating the potential to use renewable energy sources at the case study location yielded varying results. Solar energy appears to be economically infeasible for this location given the low solar energy resource, and use of PV solar panels for power generation yields an LCOE of C$0.470/kWh, nearly double that of using diesel generators. Wind energy was also investigated as a potential alternative source for power generation. The LCOE of using EWT 1.0 MW wind turbines at the case study location is expected to be approximately C$0.266/kWh, without considering the cost of batteries and power management strategy. An iterative optimization approach was used to determine the optimal number of wind turbines and battery units to be used with dual fuel generators, as an alternative power system configuration. Due to available area and wind turbine spacing requirements, seven wind turbines and three battery strings were selected as yielding the lowest LCOE, while providing approximately 10% of the mine’s electricity demand. The LCOE for this scenario is C$0.312/kWh, with a capital cost of C$23.3 million and annual operating cost of C$17.3 million. The simple payback period and annual CO₂e emission savings for this scenario with respect to the base case is 9.1 years and approximately 10,000 tonnes, respectively.
HOMER was used to validate the study results, as it is a useful tool for preliminary design and sizing of hybrid renewable energy systems. One key limitation while using HOMER is that the software does not offer dual fuel generators, therefore the validation was carried out using diesel generators. The results obtained using HOMER closely matched those from this study, with the largest discrepancy resulting from energy output of wind turbines and battery units. Integrating renewable energy components using HOMER assumes that all energy generated can be used in the power system. However, due to the smoothing effect of batteries modeled in this case study, power is discarded when wind turbine power output increases quickly, and battery units are fully charged.

Performing a sensitivity analysis on several study parameters showed that the LCOE of each scenario is most sensitive to changes in fuel prices. The effect of wind speed on LCOE for the dual fuel/wind/battery scenario was also analyzed, however LCOE appeared to be less sensitive to changes in wind speed than for changes in fuel prices. Analyzing the effects that capital cost estimates have on LCOE showed that diesel and dual fuel generator capital costs have little impact on the final LCOE. The capital cost of wind turbines for the dual fuel/wind/battery scenario produced greater LCOE sensitivity, although less than wind speed and fuel prices. This can be attributed to fuel prices constituting the majority of the total NPC of each power system configuration. An IRR sensitivity plot was investigated for the dual fuel/wind/battery scenario with respect to the base case. Wind speeds and diesel fuel prices were varied to determine the conditions that this scenario would be economically viable. It was found that average wind speeds need to exceed approximately 6 m/s or diesel fuel prices should reach at minimum C$1/L for this scenario to have an IRR greater than 10%.

Finally, the effect of a carbon tax was analyzed for each scenario, since by 2022 it is expected that a nationwide carbon tax in Canada will reach C$50/tonne. On average, the LCOE of each scenario increased by C$0.035, due to carbon tax implications. Under this assumption, dual fuel generators are economically favorable over diesel generators, offering a 4.2 year simple payback period, and NPV and IRR of C$1 million and 19%, respectively. For the dual fuel/wind/battery scenario to become competitive with diesel generators the carbon tax would need to reach approximately C$100/tonne.

The following subsections in this chapter will review the recommended options of power system configurations for the case study, and suggest aspects that require further study and measures that can be taken to mitigate future risk. Finally, a conclusion will be made summarizing the findings and considerations made from this thesis, and the broader context for similar remote mining applications.

6.1 Recommendations

Based on the findings presented in the results chapter of this thesis, there appears to be three options for power system configurations: diesel generators, dual fuel generators and a combination of dual fuel generators, wind turbines and Li-ion batteries. According to the non-carbon tax assumption, diesel generators are most favorable in terms of LCOE, although the LCOE of dual fuel generators is marginally higher. Under a C$50/tonne carbon tax assumption, dual fuel generators have the lowest LCOE, followed by diesel generators and the dual fuel/wind/battery scenario. The following paragraphs will offer further discussion, as well as recommendations for future work.

According to the results of the carbon tax analysis presented in section 5.4, dual fuel generators appear to be the most favorable option of the scenarios evaluated. Dual fuel kits used with diesel generators, or dual fuel dedicated generators for that matter are relatively
new products offered by generator suppliers. As such, there is a risk involved with pioneering a new technology in an already competitive market where mining companies are striving to minimize costs and operational concerns. In addition to diesel storage, dual fuel systems require natural gas storage and conversion units. In this case study it is assumed that natural gas is delivered to site in the form of LNG, and so vaporization units would be needed to convert this into a usable product. Therefore, careful design and planning of storage, conversion and delivery systems is required to provide accurate cost estimates, as well as safe and reliable operation.

Although dual fuel generators are more capital intensive than diesel generators, this scenario yields lower operating costs and CO₂e emissions. Furthermore, using dual fuel generators diversifies fuel sources, such that if the price of one fuel increases unexpectedly, the energy cost is more protected than if the system relied on one fuel type. There are other benefits that dual fuel systems offer with respect to diesel and natural gas dedicated systems. The main benefits include black start capabilities and grid synchronizing dynamics. To move forward with this option, further study of dual fuel market solutions could be undertaken. Dual fuel kits supplied by ComAp were targeted in this study, and future collaboration with ComAp or similar equipment providers could be established to further investigate fuel mixing potential of this option. In addition to collaborating with dual fuel kit or generator suppliers, cost information could be further delineated through vendor or contract agreements.

The second option that is proposed based on a C$50/tonne carbon tax is a conventional diesel generator system. This configuration is one typically used for remote mining operations, as it is relatively inexpensive and reliable. In comparison to duel fuel or natural gas systems that require natural gas storage, diesel storage costs are by comparison much cheaper and safer to maintain. Furthermore, given the fuel interruption risk at the case study location, diesel dedicated generators would not be at risk of fuel shortage as long as enough diesel capacity is maintained, or alternative means of delivery are available. However, this power system configuration poses the highest operating costs and annual CO₂e emissions of the scenarios analyzed. Therefore, it is most at risk of future carbon pricing and increased diesel fuel costs.

For this scenario to move forward, it is advised that several generator models be examined. Generac IDLC2000 was the model used in this case study, however CAT and Cummins also offer competitive models with costs and benefits of their own. Therefore, given the purchaser’s requirements and preferences, there are a range of diesel generator models available. Regarding capital cost and fuel prices for both the dual fuel and diesel generator scenarios, further collaboration with suppliers is recommended to determine accurate pricing and negotiate fixed price agreements for long term supply and fuel delivery.

The final proposed option is the dual fuel/wind/battery hybrid energy system. Hybrid renewable energy systems were the focus of this thesis with the aim to investigate the feasibility of employing such a system at remote locations for mining applications. Accounting for a C$50/tonne carbon tax makes this option less competitive than dual fuel and diesel generators. However, the cost of wind turbine and battery technology is rapidly improving, and costs are decreasing. Therefore, by the time that this mine is developed, the economics of this scenario may improve. This system has the highest capital cost of all options considered, and integration of multiple energy sources could be challenging and an added burden for power system operators. Furthermore, the erratic energy output from wind turbines could pose frequency and stability issues within the mine power system. However, with more study and effective use of batteries and controllers, this issue could be mitigated. It does appear for the case study location however, that the observed wind speeds are not favorable for wind energy development given their low energy output relative to the installed
power capacity.

Mining projects with higher wind speeds could make wind energy more feasible, having the potential to reduce operating costs and GHG emissions. For more serious consideration of wind energy, it is recommended that a meteorological tower be installed to capture wind speed characteristics at the expected wind turbine hub height. These measurement stations are expected to cost approximately CS$10,000 and are necessary for detailed evaluation of wind resources and further wind turbine study. Following a minimum one-year monitoring period, efforts could be made with wind turbine manufacturers to select an appropriate wind turbine model and design the optimal layout. Detailed cost estimation could follow, as well as organizing an appropriate operation and maintenance plan. The following Table 6.1 summarizes the main findings and recommendations for future work of the three power system configurations discussed above.

Table 6.1 Summary of power system options including future work recommendations, with carbon tax

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Dual Fuel</th>
<th>Diesel</th>
<th>Dual Fuel/Wind/Battery</th>
</tr>
</thead>
<tbody>
<tr>
<td>LCOE (CS/kWh)$^7$</td>
<td>0.334</td>
<td>0.336</td>
<td>0.345</td>
</tr>
</tbody>
</table>
| Pros         | -Lowest LCOE  
              -Lower operating cost and CO$_2$e emissions than diesel generators  
              -Diversifies fuel sources  
              -Diesel only if natural gas is unavailable  
 | -Lowest capital cost  
              -Reliable and experience within industry  
              -Fuel storage is inexpensive  
 | -Lowest operating cost and CO$_2$e emissions  
              -Increased carbon price improves economics  
              -See also dual fuel pros with regard to fuel  |
| Cons         | -New technology  
              -More capital intensive than diesel generators  
              -Natural gas storage is costlier and includes vaporization  
              -More complex storage and fuel transport system than diesel only  
 | -Highest operating cost and CO$_2$e emissions  
              -Diesel fuel is expensive to deliver remotely  
              -LCOE highly sensitive to changes in diesel fuel price  
              -Increased carbon price reduces economics  
 | -Highest LCOE  
              -Most capital intensive of all options  
              -Integration of renewable energy sources can be challenging and present frequency and stability issues  
              -See also dual fuel cons  |
| Future work  | -Investigate alternative dual fuel kits or designated generators  
              -Study of fuel mixing and consumption rates  
              -Further capital cost estimation  
              -Acquire fuel supply and fixed price agreements  
 | -Investigate alternative generator models  
              -Further capital cost estimation  
              -Acquire fuel supply and fixed price agreements  
 | -Install meteorological tower at expected wind turbine hub height  
              -More detailed wind turbine selection and micro-siting study  
              -Further cost estimation  
              -Operation and maintenance plan  
              -See also dual fuel future work  |

$^7$ Under CS$50/tonne carbon tax assumption
6.2 Conclusion

The objective of this thesis was to evaluate the techno-economic feasibility of using alternative energy technologies at remote mining operations for power generation, using a case study located in the Yukon territory of Canada. Diesel generators have historically, and are still the primary means of generating power at remote mining operations that do not have access to a regional electrical transmission system. Power demanded by mining operations varies depending on the type of mine and on-site infrastructure (i.e. underground vs. open pit and on-site processing requirements), and can rival that of small towns, often in the magnitude of tens of megawatts. Therefore, investigating lower cost and emission intensive energy sources is of great interest to mining companies looking to keep their operations competitive and reduce environmental impact. The alternative energy sources considered in this thesis were natural gas, wind and solar energy. Natural gas based power systems can replace diesel based ones, offering lower GHG emissions and greater opportunity to achieve higher overall efficiencies when recovering thermal energy. Given the declining costs of renewable energy technologies, as well as their potential for reducing GHG emissions and reliance on imported fossil fuels, wind and solar energy were also investigated for the case study location.

A few relevant observations can be made from the literature review chapter of this thesis with respect to mine power systems and hybrid renewable energy systems. Designing mine power systems is an important task and detailed design should commence after mine plans and equipment power requirements have been established. Once the expected load profile and electricity demand is understood, generators or other power generating sources can be appropriately selected and sized. Regarding hybrid renewable energy systems, use of renewable energy sources such as solar and wind has begun to increase in mining areas like South America and Australia, as well as on smaller scales in Canada. If grid connected, mining companies do not necessarily need to develop renewable energy technologies near their operations, and instead can develop these energy resources in better suited areas with higher wind speeds and solar radiation. Subsequently, power can be purchased from utilities, where a portion comes from renewable energy sources, and the intermittency aspect of power generation can be overcome with greater grid balancing dynamics than a standalone microgrid could provide. When access to electricity networks is infeasible, battery storage is beneficial for load balancing and supplying energy when renewable energy sources generate lower power.

The methodology taken in this thesis followed similar principals established in other HRES techno-economic assessments. The local renewable energy resources were identified through hourly wind speed, solar radiation and temperature data. System components such as diesel and dual fuel generators, wind turbines, PV solar panels and Li-ion batteries were mathematically modeled to simulate power output on an hourly basis over a sample year. To determine the optimal power system configuration for this case study, several scenarios were evaluated where diesel generators were used as a base case, and other scenarios consisting of a combination of dual fuel generators, wind turbines, PV solar panels and battery units were analyzed. The system was modeled using MATLAB and an iterative optimization approach was used to determine the optimal number of system components. The LCOE of each scenario was used as a distinguishing metric, while CO2e emissions and other economic indicators were also analyzed.

The results of the scenario analysis indicate that diesel generators offer the lowest LCOE of all configurations analyzed. However, accounting for a C$50/tonne carbon tax,
which is expected to take effect by 2022 in Canada, dual fuel generators are most economical (C$0.334/kWh), followed by diesel generators (C$0.336/kWh) and a combination of dual fuel generators, wind turbines and battery units (C$0.345/kWh). Conducting a sensitivity analysis determined that fuel prices have the greatest effect on LCOE, which suggests that long term purchasing agreements could reduce some risk associated with fuel. Further collaboration with dual fuel kit and generator providers is also recommended to further delineate fuel consumption rates and cost estimations.

The findings of this thesis indicate that renewable energy such as solar and wind are not economically attractive options for the case study location, under current market conditions and assumptions made. The LCOE of solar energy was found to be approximately double the cost of fossil fuel generators, due to low solar radiation received at the case study site. The optimal dual fuel, wind turbine and battery configuration was calculated as being slightly more expensive than the fossil fuel generator scenarios, where wind turbines generate approximately 10% of electricity consumed. The economics of solar and wind energy improve in areas where higher solar radiation and faster wind speeds are experienced. Therefore, mining areas that have access to higher quality renewable energy resources could make these options economically viable. Furthermore, natural gas generators could act as alternative means of power generation for remote mine sites that expect reliable delivery of fuels, and thereby decrease operating costs and GHG emissions further than what was achieved in this case study. Finally, although this thesis targeted power generation, there are other methods that can reduce fossil fuel consumption and improve energy efficiency. Recovering thermal energy from power generation and other exothermic processes is one such option, as well as more efficient energy management strategies and electrifying mining equipment where possible.
Bibliography


REC Group. (n.d. (b)). REC Twinpeak 2S 72 Series Data Sheet.


# Appendix A Mine-Power Benchmarking

Table 6.2 Raw data from mine power benchmarking analysis

<table>
<thead>
<tr>
<th>Mine</th>
<th>Location</th>
<th>Mining rate (tpd)</th>
<th>Ore type</th>
<th>Mining method</th>
<th>Power capacity (MW)</th>
<th>Grid connected?</th>
<th>Description</th>
<th>Reference</th>
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<tbody>
<tr>
<td>Wolverine</td>
<td>YT</td>
<td>1,700</td>
<td>Zn, Cu, Pb, Au, Ag</td>
<td>U/G</td>
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<td>No</td>
<td>Diesel generators</td>
<td>(Regan, 2007)</td>
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<td>Minto</td>
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<td>Cu, Au, Ag</td>
<td>O/P, U/G</td>
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<td>(Doerksen, et al., 2008)</td>
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<td>Mahtung</td>
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<td></td>
<td>W</td>
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<td>Yes</td>
<td>Yukon electric grid</td>
<td>(Narciso, et al., 2009)</td>
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<tr>
<td>Eagle Gold</td>
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<td>Au</td>
<td>O/P</td>
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<td>Yes</td>
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<td>(Doerksen, et al., 2016)</td>
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<td>Keno Hill Silver District</td>
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<td>Au, Ag, Pb, Zn</td>
<td>U/G</td>
<td>n/a</td>
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<td>(Jensen, Arseneau, Austin, Bergen, &amp; Farrow, 2017)</td>
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<td>No</td>
<td>49 MW Diesel 9.2 MW Wind</td>
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<td>Gahcho Kue</td>
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<sup>8</sup> n/a – information not available
Appendix B HOMER User Inputs

Table 6.3 HOMER Pro microgrid software user input summary

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<th>Project</th>
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<tr>
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<td>Project lifetime (years)</td>
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<table>
<thead>
<tr>
<th>Electric load</th>
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<tr>
<td>Average (kW)</td>
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<table>
<thead>
<tr>
<th>Generator</th>
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<tr>
<td>Name</td>
<td>Generic Large Genset (size-your-own)</td>
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<td>Capacity (kW)</td>
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<td>Operating (CS/hr)</td>
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<td>Fuel curve</td>
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<td>Intercept coefficient (L/hr)</td>
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<td>Slope (L/hr/kW)</td>
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<thead>
<tr>
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<td>EWT DW 61 [1000 kW]</td>
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<td>Rated capacity (kW)</td>
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<td>2,000,000</td>
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<td>Operating (CS/year)</td>
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<td>CanadianSolar MaxPower CS6U-340M</td>
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<td>Panel slope (degrees)</td>
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<td>Panel azimuth (degrees)</td>
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<tr>
<th>Storage</th>
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<tbody>
<tr>
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<td>Generic 100 kWh Li-ion</td>
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<td>Nominal capacity (kWh)</td>
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<tr>
<td>Round trip efficiency (%)</td>
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<td>Capital (CS)</td>
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