UNIVERSITY OF CALGARY

"Exploring Renewable Energy Opportunities for Nunavut"

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A RESEARCH PROJECT SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE

GRADUATE PROGRAM IN SUSTAINABLE ENERGY DEVELOPMENT

CALGARY, ALBERTA

AUGUST, 2018

Abstract

The Canadian territory of Nunavut covers one fifth of Canada's landmass and, without a road network or linked power grid, residents rely exclusively on off-grid diesel generated power stations to supply electricity. Once considered convenient, these systems have now become inefficient and difficult to maintain. Economic, environmental, and social analyses must be conducted in order to recognize the viability of developing clean, renewable, and sustainable energy in the territory. For the community of Rankin Inlet, this involves understanding the benefits of reducing harmful diesel fuel emissions. Simulations of potential wind and solar power plants help to create an understanding of the economics behind such a project. This research focuses on answering the question "should renewable energy be considered as a replacement for the ageing diesel generation stations in parts of Nunavut?" Results suggest that hybrid generation systems are a viable and feasible approach to the future of power generation in Rankin Inlet.

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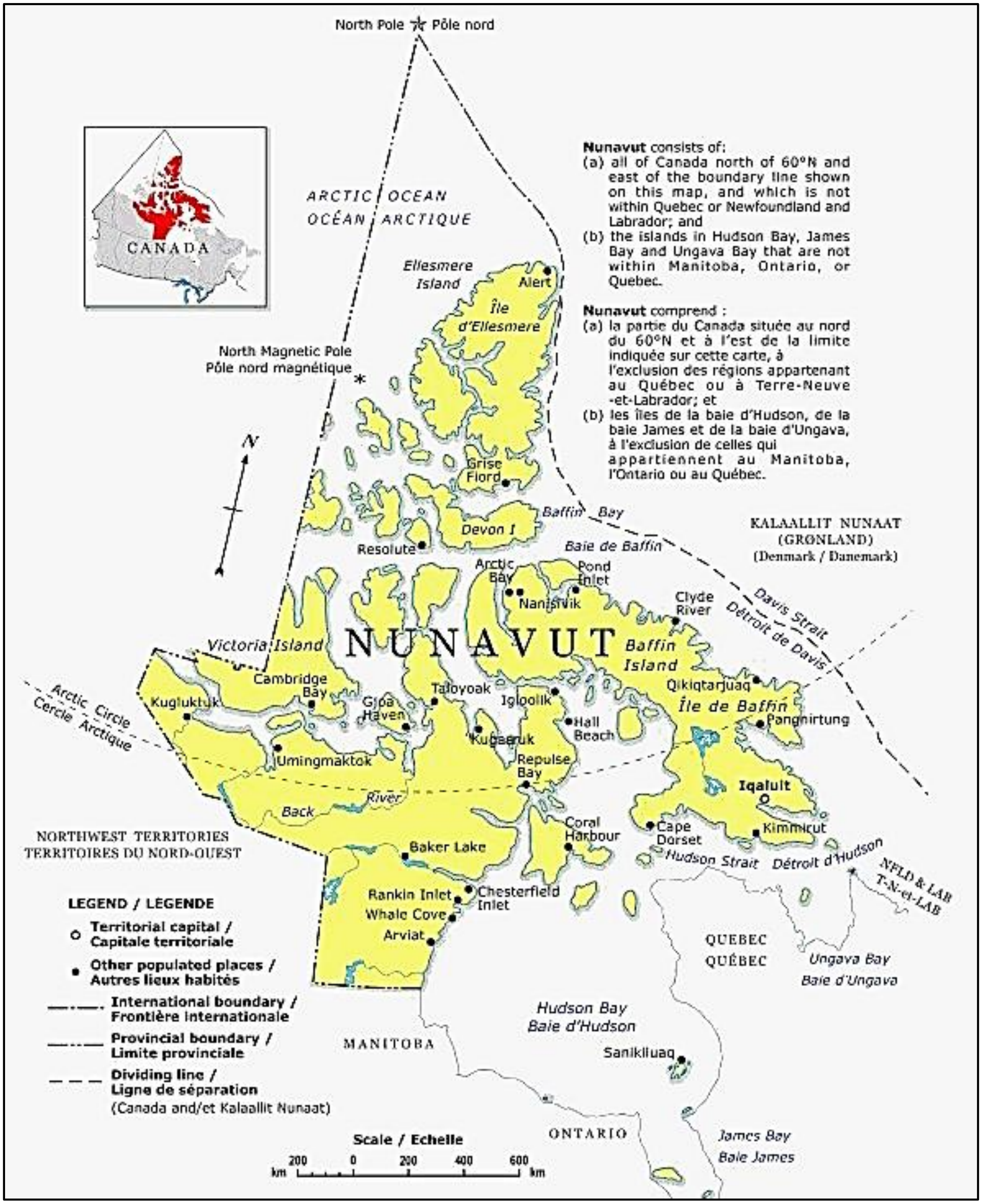
Chapter 1: Introduction

1.1 Overview

The Canadian territory of Nunavut has an outdated and inefficient energy generation system. This is mainly due to the fact that it is the only administrative division in Canada that does not have a developed source of primary energy production. All other provinces and territories extract petroleum resources and harness natural energy to produce electricity that supplies a local power grid. In Nunavut, off-grid mechanical diesel electricity generators are used exclusively to supply power, which results in approximately 36,000 people relying heavily on external fuel supplies. This system requires very large quantities of fossil fuel in order to maintain the basic living amenities for its people. Each community in Nunavut has its own independent diesel electricity generation and distribution system and there is no back-up grid (Nunavut Dept. of Environment, 2018). There are no interconnecting road systems in Nunavut so fuel has to be shipped along the jagged coast during ice-free summer months and eventually stockpiled at designated distribution centers. Therefore, it is important propose and develop new energy solutions, and to encourage renewable energy options that move towards power diversification, energy independence, and enhancing environmental awareness. This research investigates wind and solar electricity generation potential in an effort to answer questions concerning resource availability, technological requirements, and costs associated with creating the most effective renewable energy project for the town of Rankin Inlet, Nunavut (Figure 1).

The Qulliq Energy Corporation (QEC) is the governing body responsible for generating electricity and maintaining all the diesel plants in the territory's 25 communities. Providing power costs the Government of Nunavut nearly $200 million in fossil fuel annually. This combined with distribution expenditures totals approximately $350 million per fiscal year, a number that is steadily rising (Government of Nunavut, 2017). For this type of system, the electricity generation costs are higher than the rest of the country and can vary significantly. In Arctic, electricity rates can range from $0.49/kWh to $2.50/kWh, while for the rest of Canada the average electricity rates range from $0.07/kWh to $0.17/kWh (Arriaga, M., Canizares, C., & Kazerani, 2014).

Figure 1: Map of Nunavut



(Government of Canada, 2018a)

Changing the way the Nunavummiut look at energy is now a government initiative. The QEC and other territorial governing bodies such as the Department of Community Services, Nunavut Housing Corporation, Nunavut Department of Finance, and Nunavut Department of Environment have structured several energy saving initiatives and incentives in an effort to educate citizens and curb excess power usage. Entrepreneurial programs such as the ecoENERGY for Aboriginal and Northern Communities Program (EANCP) and Strategic Investment in Northern Economic Development (SINED) have been focusing on providing funding support to Aboriginal and northern communities for renewable energy projects and economic diversification.

Nunavut has an array of unharnessed renewable energy potential. In Cumberland Sound, on Baffin Island, winds are favorable for turbine installation (*wind atlas* from Government of Canada, 2018b). This resource is just 100 km north of the town of Iqaluit (Figure 1) which is the most populated and energy consuming community in the territory. Near the town of Chesterfield Inlet on mainland Nunavut, the annual potential photovoltaic energy capture is greater than that of Victoria, BC, and the town of Arviat has tremendous potential for wind harnessing. Utilizing renewable energy has been attempted here in the past, but encountered mixed results, with some projects operated for a short period before eventually being decommissioned (Nunavut Dept. of Environment, 2018). Since the timing of these projects, significant improvements have occurred in renewable energy technology and generating capabilities. With available access to more robust and efficient equipment, the QEC is now planning to install wind resource monitoring towers at potential project sites in order to gain accurate data. To date, two monitoring towers are scheduled for installation, one in Cape Dorset and one in Arviat. This is the beginning of a new outlook on harvesting renewable energy in the Arctic.

From a societal perspective, the need for diesel continues to force these isolated northern communities to be dependent on the outside world for fossil fuel. Even worse, the financial demand associated with powering a fossil-fueled grid is depleting funds that would be better put to use supporting important social programs. “This reality provides many challenges for Nunavut moving forward. Energy expenditures are non-discretionary budget items, and as such, any increase in energy prices directly impacts the funding of priorities such as health, education, and housing” (Government of Nunavut, 2017, p. 1). Replacing, or at least incorporating sustainable energy into communities, will not only provide a buffer between the unpredictable prices of the petroleum market, but would also help develop other important public services required for residents. A community entirely powered by wind and/or solar power could also help encourage innovation and support a self-sustaining environment that aligns with the core beliefs of the Nunavut Inuit people.

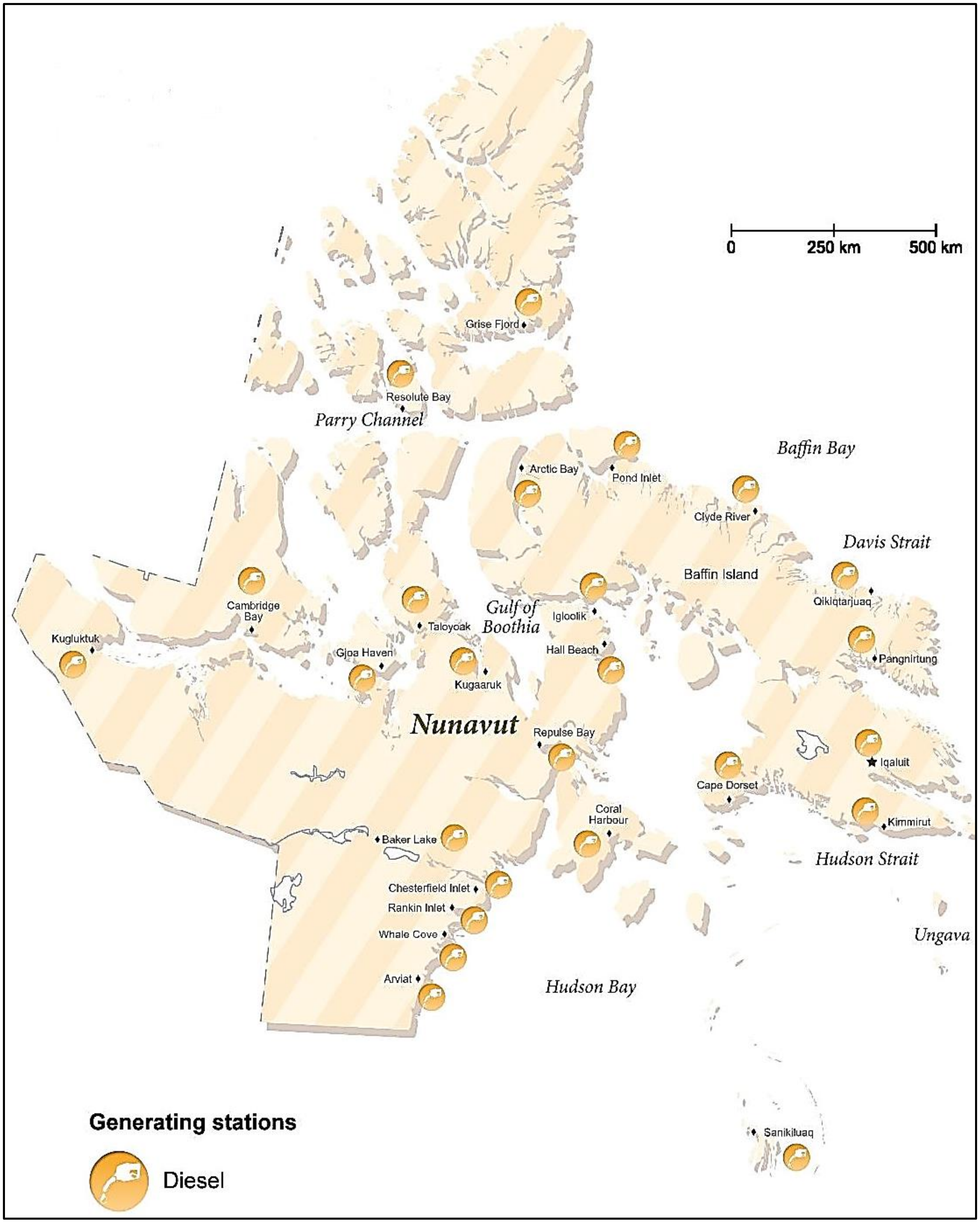
In order to advance the concept of energy independence, energy modelling and project proposals should be executed in a manner that centers on renewable power grid incorporation. This can be conducted by analyzing the shortcomings of past projects, the natural power availability, and the cost-benefit analysis of new installations.

With nearly $200 million worth of diesel fuel consumed annually, small northern Indigenous communities are forced into having large financial and environmental footprints. With the newly introduced greenhouse gas (GHG) emission limitations and the Federal Carbon Pollution Pricing System, the QEC and other developers will likely be looking to these isolated, diesel-dependent communities to invest in renewable energy infrastructure and technology. Identifying Nunavut as having the potential to be an exemplary location for sustainable electricity generation is necessary in order to begin an energy paradigm shift that will lower the economic burden of this heavily subsidized territory.

1.2 Diesel Electricity Generation and Issues

Remote, off-grid communities throughout Nunavut use diesel fuel generator sets to produce electricity (Figure 2). Depending on the size of the community, multiple generator sets may be required to accommodate peak load demand. These systems also require a stand-by generator that has the capacity to produce enough electricity to handle critical load requirements during maintenance periods. A diesel generator can operate reliably in any location as long as there is a steady fuel supply, with some running for up to 99.9% of the year. Fuel consumption for electricity generation in Nunavut is in the tens of millions of liters and the current power plant are without energy storage options. This all combines to form a steadily running, poorly efficient, fossil fuel combustion engine that is costly to operate and maintain.

*Figure 2: Overview of Nunavut's Diesel Generators * as of 2015*



(Government of Canada, 2015)

For several decades this has been the most feasible option for northern communities. Among the early benefits were ease of installation, as well as consistent operation, which allowed for quick grid setup and minimal maintenance requirements. Nearly 60 years ago, when diesel generators were introduced into Canada's Arctic, they were the latest technology and the best possible solution for remote areas. With the passage of time, the ageing equipment has become less reliable and operational costs began to rise dramatically. Having such a large fleet of ageing diesel facilities requires the QEC to commit significant portions of capital spending to replacing components to extend operational life. Acquiring parts for these ageing plants is a constant challenge and increases the risk of power outages. Table 1-1 shows the age and years remaining on operation life of these generators.

*Table 1-1: Age and Remaining Life of Nunavut's Diesel Generators * as of 2014*

Plant Name	Constructed	Remaining Life
Grise Fiord	1963	0
Qikiqtarjuaq	1936	0
Cape Dorset	1964	0
Cambridge Bay	1967	0
Kugluktuk	1968	0
Arviat	1971	0
Pangnirtung*	1971	0
Resolute Bay	1971	0
Taloyoak	1972	0
Rankin Inlet	1973	0
Arctic Bay	1974	0
Hall Beach	1974	0
Igloolik	1974	0
Kugaaruk	1974	0
Chesterfield Inlet	1975	1
Gjoa Haven	1977	3
Coral Harbour	1988	14
Whale Cove	1991	17
Kimmirut	1992	18
Pond Inlet	1992	18
Clyde River	1999	25
Naujaat	2000	26
Sanikiluaq	2001	27
Baker Lake	2003	29
Iqaluit	2014	40

(Government of Nunavut, 2017)

Diesel as a fuel source is combustible but not flammable and, as a result, relatively safe when comparing it to gasoline and natural gas, thus making it the better fossil fuel for transportation and storage. This safety factor combined with its high energy density has made diesel a modern global necessity. In 2016, wholesale diesel ranged on average from $0.90-1.00per liter in Canada with costs fluctuating due to a number of economic, political, and supply factors. The cost of crude oil is the largest component of the retail price of diesel. Worldwide supply determines crude oil prices and global economic conditions contribute to the demand for petroleum products made from crude oil. The U.S. governmental Energy Information Administration predicts that the cost of crude oil and diesel fuel will continue to rise as demand increases due to increasing global population. This inconsistency in price can lead to these off-grid systems having an unpredictable growing fuel budget. In 2002, the cost of operating Nunavut's energy grid was approximately $121 million, a number that has since tripled (Government of Nunavut, 2017).

To keep electricity rates affordable for Nunavut community residents, the government operates the Nunavut Electricity Subsidy Program, which provides a subsidy at 50% of the Iqaluit rate, which turns out to be around $0.60 per kWh. In addition, all residents who live in public housing (52% of the Nunavut population), have rates capped at $0.06 per kWh. "As such, electricity is dramatically subsidized by government, thereby perpetuating diesel fuel consumption and reducing the imperative to support clean power projects" (Pembina Institute, 2016, p. 64). Table 1-2 shows the cost breakdown and GHG impact resulting from diesel consumption. This data does not include the transportation cost of shipping diesel to remote communities, an expense that exceeds the annual costs of fuel purchases in some towns.

Table 2-2: Summary of Utility Fossil Fuel Generation Costs for Nunavut Communities

Territory	Reference Year	Community	Fossil Fuel Generation (MWh)	Plant efficiency (kWh/l); (kWh/m3)	Fuel Price ($/l); ($/m3)	Fossil Fuel Cost per Unit of Generation ($/kWh)	Non Fuel Operating Costs: Average Overhaul Cost ($/kWh)	Non Fuel Operating Costs: Non-fuel O&M ($/kWh)	Capital Component ($/kWh)	Total Utility Costs ($/kWh)
Nunavut	2014/15	Iqaluit-Diesel	60,741	3.82	1.11	0.29	0.03	0.09	0.09	0.50
	2014/15	Cambridge Bay-Diesel	10,267	3.69	1.08	0.29	0.03	0.09	0.09	0.50
	2014/15	Rankin Inlet-Diesel	17,625	3.77	1.06	0.28	0.03	0.09	0.09	0.49
	2014/15	Baker Lake-Diesel	9,518	3.86	1.06	0.27	0.03	0.09	0.09	0.48

(Bullfrog Power, 2017)

Table 3-3: Estimated GHG Emission Cost of Fuel Generation

Territory	Community	Fossil Fuel Generation (MWh)	Total Utility Current Costs ($/kWh)	Potential Impact of GHG Cost: GHG Cost based on $10/tonne		GHG Cost based on $50/tonne	
				($/kWh)	% impact	($/kWh)	% impact
Nunavut	Iqaluit-Diesel	60,741	0.50	0.01	2.0%	0.05	10.0%
	Cambridge Bay-Diesel	10,267	0.50	0.01	2.0%	0.05	10.0%
	Rankin Inlet-Diesel	17,625	0.49	0.01	2.0%	0.05	10.2%
	Baker Lake-Diesel	9,518	0.48	0.01	2.1%	0.05	10.4%

(Bullfrog Power, 2017)

Diesel fuel consumption generates GHG emissions that have negative implications on the atmosphere (Table 1-3). Environment Canada lists diesel fuel as having an emission factor of 2663 g/L CO_2, 0.133 g/L CH_4, and 0.4 g/L of N_2O (Environment Canada, 2011). Each of these compounds contribute to the greenhouse effect and have measurable global warming potential (GWP) values, as defined by the International Panel on Climate Change (2007). After factoring in all GWP values and normalizing it to CO_{2eq}, diesel fuel has an emission factor of 2785.5 g/L. In 2012-2013, Nunavut consuming 44 million liters for their electricity grid (Government of Nunavut, 2017) which results in 121,242 tonnes of CO_2 released into the atmosphere. Rankin Inlet, the study area for this project, requires 14 million liters of diesel fuel to electrify and heat the community annually. Consumption results in each resident emitting an average of 24 tonnes of CO_{2eq}

annually, a value that is 60% more than the national average of 15.1 tonnes per capita (Government of Canada, 2018).

A federally-imposed carbon tax designed to reduce the use of climate-warming fossil fuels will soon see people in Nunavut paying more for electricity. For customers, this tax means that power bills will increase by an average of about $100 per year and the additional amount that customers will pay will likely increase to $700 a year by 2022 (Nunatsiaq News, 2018). This is a result of the recently signed Pan-Canadian Framework on Clean Growth and Climate Change agreement. The agreement calls for carbon-producing fuels, including diesel, to face an additional tax of $10 per tonne starting in 2018. That surcharge could rise to $50 per tonne of emissions by 2022. Provinces and territories that do not create their own carbon pricing system, either through a direct carbon tax or a cap-and-trade market system, will have a "backstop tax" imposed on them.

> "All elements of the backstop (tax) will apply in a jurisdiction that does not have a carbon pricing system in place. The backstop will also supplement systems that do not fully meet the benchmark. For example, the backstop could expand the sources covered by provincial carbon pollution pricing or it could increase the stringency of the provincial carbon price. As committed in the October 3, 2016 document Pan-Canadian Approach to Pricing Carbon Pollution, the federal system will return direct revenues from the carbon price to the jurisdiction of origin. The federal government is open to feedback on the best mechanism to achieve this" (Department of Environment and Climate Change Canada, 2018, p.1).

Other issues with diesel consumption involve transporting it to remote locations within the territory. The Nunavut Petroleum Products Division (PPD) purchases fuel in the summertime during sea transport season when ships can move through ice-free waters. PPD buys Nunavut's petroleum products under supply and transportation contracts and fuels are typically sourced from refineries on the East Coat of Canada, the United States or, in some cases, overseas countries such as Finland or Japan. All bulk fuels are transported to Nunavut from the East Coast of Canada via oceangoing vessels that deliver the cargo to the northern coastal communities. Occasionally this long distance shipping process can be problematic. In 2010 a tanker contain 9.5 million liters ran aground near the hamlet of Gjoa Haven, and that same year another tanker grounded near Pangnirtung on southern Baffin Island. No spills were detected and the potential for devastation was avoided. The Spill Contingency Planning and Reporting Regulations for Nunavut include the requirement for an emergency response plan to be prepared and filed for facilities where petroleum, chemicals and other contaminants are stored. This plan is supported by the Environmental Protection Act and identifies proper authorities by outlining reporting and communication procedures that support an action plan in the event of a spill. Although mitigation measures are in place this does not eliminate the threat of environmental contamination.

With increasing concern for diesel usage, an Energy Strategy for Nunavut (Ikummatiit) was passed in 2007 that provides guiding principles for Nunavut's energy policies and related Government programs and activities into the year 2020 (Government of Nunavut, 2007). Ikummatiit has four main objectives:

> 1) Improve the security of the energy system by reducing reliance on imported fossil fuels, diversifying energy supply to include clean, alternative energy and domestic energy sources.
>
> 2) Manage the cost of energy-based services such as transportation, heating, hot water, lighting, and cooking, by reducing the cost of providing energy and improving the efficiency of its use.
>
> 3) Reduce the impact on the environment by reducing energy-related emissions which contribute to pollution and climate change.
>
> 4) Provide business and employment opportunities as the Territory increases energy efficiency and uses renewable and domestic energy sources.

1.3 This Study

Nunavut's energy challenges stand apart from its provincial and territorial counterparts. The Government of Nunavut is under constant pressure to supply consistent electricity to homes while maintaining outdated equipment, thus making inhabitants deeply dependent on the actions and policies of the QEC. High dependency on social assistance conflicts with the strong sense of values, resilience, and sustainability that have endured with the Nunavut Inuit culture for centuries. In order for renewable energy to penetrate the Nunavut off-grid power system, research must be conducted in an effort to outline electricity generation techniques that have the right combination of operational reliability, affordability, and efficiency.

The main objective of this research project is to identify and analyze areas in Nunavut where wind and/or solar electricity generation can be used to lessen the need for expensive diesel power generation.

The area near Rankin Inlet has high potential for wind electricity generation that, if utilized properly, could aid in decreasing the more than $12,000 per resident being annually on supporting the current system. Through a cost-based approach, this study will examine whether it is feasible to replace the ageing diesel power plants with a system with new generators combined with wind and/or solar power generation.

This research project will take on a multi-disciplinary approach and focus on the three pillars of sustainability. Environment and energy balance will be the initial consideration with an analysis of electricity demand versus potential renewable energy availability. The study will look at economic feasibility over the life span of the project, which is estimated to be 20 years. The social pillar will be examined by outlining the benefits that energy independence could have for Indigenous communities. A key question to be asked is: "Could developing sustainable energy resources create a more modernized northern community with advanced social programs paid for by money saved due to reduced fossil fuel usage?" Other questions to be addressed include: "What technology best suits the physical conditions of Rankin Inlet?" and; "How can we learn from other renewable projects that have recently been developed in the Arctic?"

Chapter 2: Nunavut and an Enhanced Standard of Living

2.1 Nunavut Territory and Self-sufficiency

Prior to 1999 the territory of Nunavut was part of the Northwest Territories. In 1993, Canada incorporated two pieces of legislature that help create the Nunavut territory, The Nunavut Land Claims Act (NCLA) and the Nunavut Act. The NCLA was agreed upon and signed by the territorial Inuit and was based on 4 objectives:

> (a) To provide for certainty and clarity of rights to ownership and use of lands and resources and of rights for Inuit to participate in decision-making concerning the use, management and conservation of land, water and resources, including the offshore;
>
> (b) To provide Inuit with wildlife harvesting rights and rights to participate in decision-making concerning wildlife harvesting;
>
> (c) To provide Inuit with financial compensation and means of participating in economic opportunities; and;
>
> (d) To encourage self-reliance and the cultural and social well-being of Inuit (Nunavut Tunngavik Incorporated, 2018, p.1)

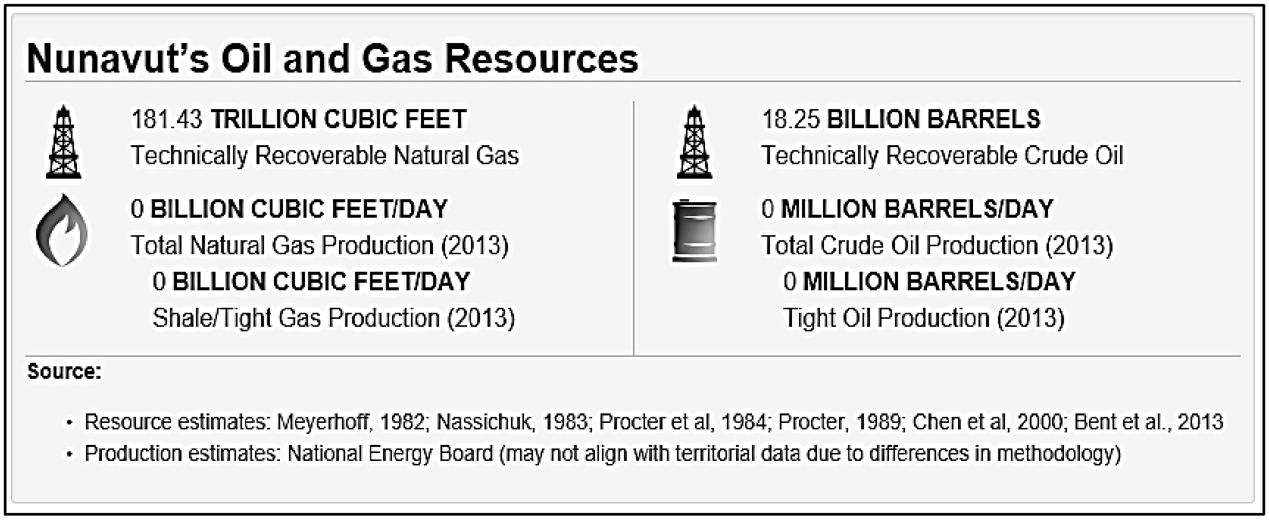
Upon separating with the Northwest Territories in 1999, discussions initiated the topic of devolution of rights between the Government of Canada and the Government of Nunavut, wherein a transfer of federal jurisdiction over the territory's lands, resources, and inland waters to the Territory would be established. There still remains no concrete agreement in place that legislates this authority. An agreement, as such, is essential for the territory to control natural resources and to develop Nunavut's energy potential and self-reliance. The NCLA and Nunavut Act followed a historical, fossil fuel-based and extractive mindset and largely ignores the energy potential of renewables (McDonald, 2011).

2.2 Powering the Tundra

In 1948, with the rapid expansion of the mining sector, the Canadian government recognized the need for an integrated utility industry in the north. An Act of Parliament established the Northwest Territories Power Commission, renamed the Northern Canada Power Commission (NCPC) in 1956. Diesel power plants were installed and owned by the NCPC before being transferred to the territorial governing body, but not before other more controversial options were considered. During the 1970’s, there had been suggestions of NCPC employing "slowpoke" nuclear generators to produce power in the many isolated communities. “Slowpoke” micro-nuclear reactors are a low-energy nuclear reactor designed by Atomic Energy of Canada Limited (AECL) in the late 1960’s for research purposes. “While traditional nuclear plants produce upwards of 1,000 megawatts of electrical power, far too much for a small community to use economically, smaller designs in the 10 MW range could power larger, off-grid towns effectively and with purportedly few of the traditional dangers associated with larger reactors” (CBC, 2011, p.1). The economics of this type of system were estimated to be competitive with that of conventional fossil fuels, however, the market for this technology did not materialize. With the price of fossil fuels continuing to rise, this idea once again has gained attention.

Nunavut communities are currently all off-grid with no connections to North American electricity or natural gas grids. Low population, severe weather, and remoteness make long distance high voltage grids unviable. Therefore, fossil fuels are needed. While Nunavut holds abundant offshore oil and gas deposits, no wells have been brought into production (Figure 3).

Figure 3: Fossil fuel reserves in Nunavut



(NRCan, 2018a)

All of Nunavut's diesel power plants fall under the jurisdiction of the QEC. With headquarters in Baker Lake, the organization is responsible for operation and maintenance of equipment throughout the territory. The QEC was established by the Nunavut Power Utilities Act in 2001, two years after the 1999 creation of the territory. Originally named Nunavut Power Corporation, it was renamed in 2002 with the mandate of the corporation expanding to include energy conservation and alternative generation development. The QEC established the Nunavut Energy Centre in 2006 as a division focusing on energy conservation through public outreach. The centre was closed down on March 31, 2009, and its functions were transferred to territorial government departments in a move to focus solely on the business of power generation.

As of 2014, there are approximately 17 diesel power plants that had reached the end of their designed service life. Because of this, the QEC is considering a new approach to the future of electricity generation. The current vision statement reads: "Qulliq Energy Corporation's vision is to provide the communities of Nunavut with safe, reliable, sustainable and economical energy supply and service. Our foundation to achieve our vision is based on an empowered and accountable workforce, representative of Nunavut's population, and reflective of Inuit Societal Values" (QEC, 2018, p.1).

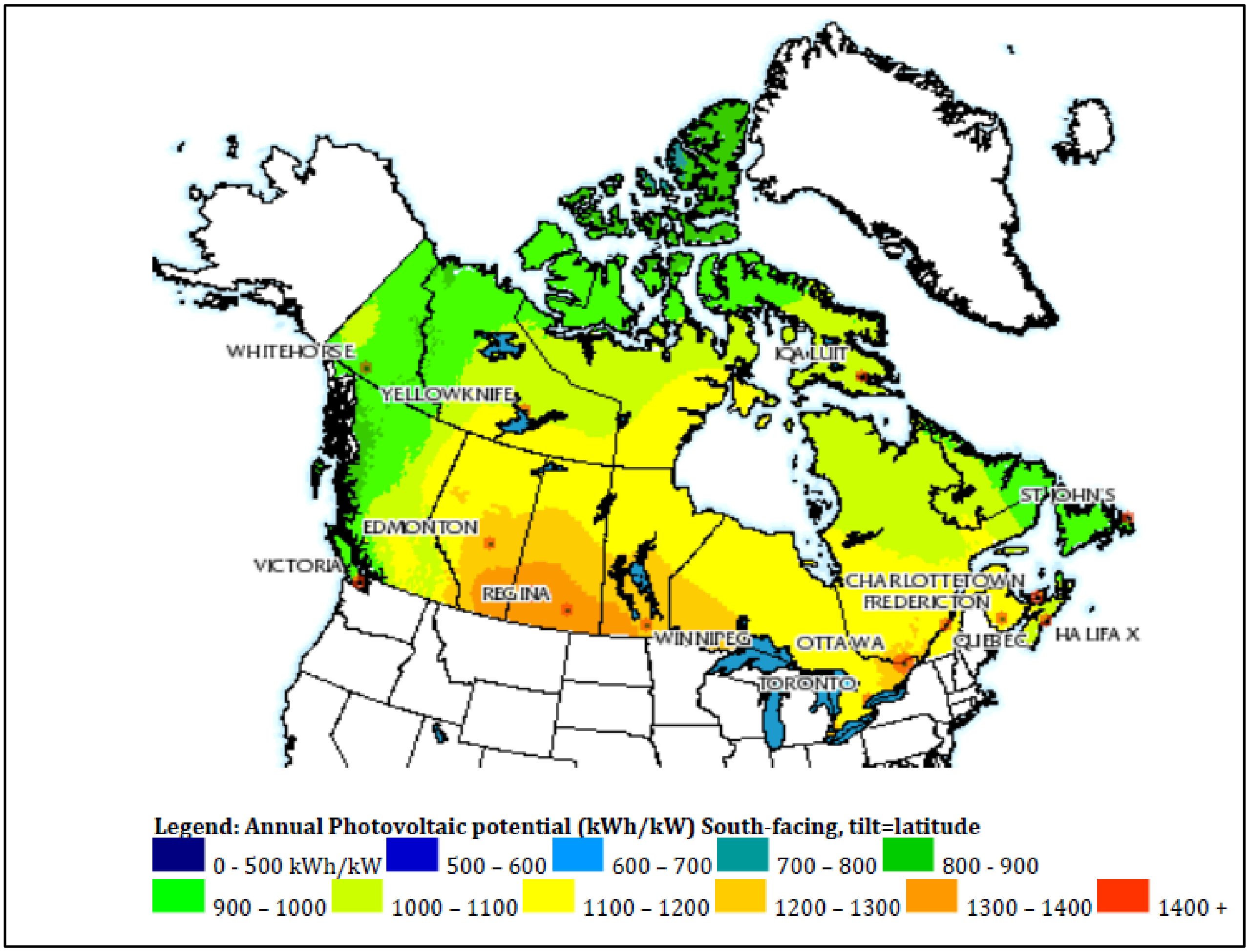
2.3 Renewable Energy in the North, Past to Present

Wind power has historically been the most researched renewable energy source in Nunavut. Since the early 1980's, projects have been proposed and tested for some of the windiest parts of the territory, and from 1985-1994 there were several studies conducted to test the viability of a diesel generation system backed up by wind turbines. These early tests supported the installation of a wind turbine in Cambridge Bay in 1994 that operated until 1999, and two turbines in Kugluktuk that ran from 1997 to 2002. Rankin Inlet has also been an attractive target for wind-powered electricity generation, and in 1998 the town was chosen for a test installation to collect data that could help understand the viability of wind infrastructure. A single 50 kW turbine was eventually erected that produced 80 MWh at 36% wind availability from the months of November 2000 to December 2001. The generation of 80 MWh of wind electricity displaced approximately 20,000 liters of diesel fuel from the power grid (WEICan, 2009). However, issues did arise when the turbine was left inoperable due to lack of maintenance personnel. The QEC decided that only having one turbine does not justify having full-time qualified maintenance personnel, and it was stated that their support for wind power strongly depended on the current price of diesel fuel.

Recently, companies have been experimenting and implementing clean energy in Canada's Arctic. In 2014, TUGLIQ Energy, based in northernmost Quebec, constructed the Glencore Raglan Mine Renewable Electricity Smart-Grid Pilot Demonstration, a 120 metre high wind turbine and battery storage facility. Most mine sites are heavily dependent on diesel, making fuel cost a significant expense. This turbine takes advantage of the high winds in the area, and has saved the mine about 2.1 million litres of diesel in its first year of operation. The company estimates that the install will save more than $40 million in fuel costs over the next 20 years. TUGLIQ Energy has stated that the same technology would work in remote areas of the Arctic and they want to do business with mine sites in Nunavut" (CBC, 2016b, p.1).

Photovoltaic (PV) energy capture also has potential in the north. Locations along Hudson Bay receive the highest amount of solar energy in Nunavut (Figure 4). The annual sun exposure here is comparable to the amount of sunshine that reaches southern Quebec, much of Ontario, and the Maritimes. Solar PV applications have already demonstrated success in parts of Nunavut. A PV array at the Arctic College in Iqaluit has delivered electricity since its installation in 1995.

Figure 4: Annual Photovoltaic potential for Canada



(NRCan, 2018b)

Large-scale solar projects have been implemented in northern communities as of late. Colville Lake, high in the Northwest Territories, has successfully tested a system of batteries and solar panels that allows the community to run entirely on the sun's energy for periods throughout the summer. The town, a Dene community of about 150, recently replaced its aging diesel generator. Once the town installed the generator it was supplemented with an array of solar panels capable of generating 136 kilowatts and batteries that store 200 kWh. In the dark winter months Colville Lake runs entirely on diesel, but during the summer months enough solar energy is captured and stored to supply adequate electricity (CTV, 2016). Currently, 1/5 of the town's annual energy use comes from the sun, even though the panels produce almost nothing between November and January. The batteries allow more efficient operation of the diesel generator and enhance the electricity generated by the solar PV system, minimizing the impacts of system maintenance and smoothing out the load delivery required by the generators. This results in lower maintenance and extends the useful life of the generators. The Northwest Territories Power Corporation estimates that it saved 37,000 liters of diesel fuel just from solar generation in the first year. It has been reported as a “vast improvement” over the old generation system with locals appreciating the reduction in noise pollution caused by the constantly running old system (CTV, 2016, p.1). This project validates the technical and economic feasibility of integrating solar PV with significant battery storage and serves as a benchmark for the amount of renewables that can be integrated successfully into an off-grid location in Nunavut.

Other renewable energy options have also been considered. The QEC has recently designed a hydroelectric project that could produce between 16-25 MW for the town of Iqaluit. Capital costs for the project were estimated at $250-$450 million, and as a result, the territory's finance minister decided to put it on a hiatus, as it was deemed too expensive for an energy project that would only supply 8000 people. A more indirect approach to utilizing hydropower was recently considered when a transmission project was proposed that would connect a power line between mainland Nunavut and Manitoba. Both governments have renewed a memorandum of understanding on a transmission line that would deliver hydroelectric power to Arviat and Rankin Inlet (CBC, 2016b).

With momentum building towards a shift to renewables, policies are taking form that outline strategic objectives to improve energy system security, reduce reliance on fossil fuels, manage costs, reduce environmental impact, and provide new business and job opportunities. Recent decisions to develop net metering and independent power production policies (IPP) are considered ground-breaking. In the past, the Qulliq Energy Corporation Act, did not allow non-QEC entities to generate power but with this new strategy there has been positive change. The public is responding and the IPP is opening the door for people who create their own power using solar panels by helping them send excess energy to the community's power grid. Residents get a credit on their energy bill for the excess power they generate while using renewable sources. This type of net metering program is for customers who generate up to a maximum of 10kW of power. However, there is a limitation for the system and how much it can accept and, therefore, it only allows a certain number of people to take part in the program in each community. “QEC is also involved in preliminary discussions with the territorial government about purchasing power from businesses that generate renewable power, or investing in its own renewable technology options” (CBC, 2016d, p. 1).

2.3.1 Outside Interests

The Arctic has been a target area for many ENGO’s and research institutes that strive to emphasize the relationship between climate change and renewable energy. Organizations such as the World Wildlife Fund (WWF) and the Pembina Institute have been stressing the importance of de-carbonizing Arctic electricity for several years. The growing interest in researching clean energy options for the Arctic has led to several revealing studies that support the ideas of this project.

In 2016, the University of Waterloo prepared a pre-feasibility report (Das & Canizares, 2016) for the WWF highlighting that renewable energy usage can provide 35% of the overall power supply in the five largest Nunavut communities. The restructuring would involve building a hybrid-diesel system with the existing power plants as a way to keep overall costs low. The objectives of the study were stated as follows: 1) Determine 5-6 communities suitable for feasibility studies that will be used to build business cases for renewable energy deployment; 2) rank communities based on several criteria, such as project investment cost versus O&M savings or replacement of required diesel generators, at minimum costs and; 3) displace diesel fuel, not existing diesel capacity, by incorporating wind and solar plants and battery storage systems, so that local grids can be securely operated. The study selected communities that had the highest cost of energy combined with the most demand and highest access to renewable clean energy. Other costs such as equipment purchases, transportation, purchase points, and age of current generators were considered. Findings in this report concluded that the most suitable communities for renewable installations to be Sanikiluaq, Iqaluit, Rankin Inlet, Baker Lake, and Arviat.

2.3.2 Federal Support

Supporting Indigenous communities in clean power projects has been, and continues to be, a major objective of federal governance. The Government of Canada has provided funding through several departments, including Natural Resources Canada's (NRCan) ecoENERGY for Aboriginal and Northern Communities program, and Indigenous and Northern Affairs Canadas (INAC) Community Opportunity Readiness Program. Ottawa also provides loan support through various business programs targeting Indigenous entrepreneurs, as well as research and development support through programs including Sustainable Development Technology Canada.

As of 2015, the Canadian Energy Strategy includes a specific mention on reducing diesel reliance in off-grid communities. In July 2015, a Pan-Canadian Task Force consisting of all provinces and territories was created to tackle diesel fuel dependence in remote communities (Pembina Institute, 2016). In August 2016, NRCan announced the Energy Innovation Program with the objective to support energy technology innovation in northern communities. "Promises to ramp up infrastructure spending and accelerate the transition to cleaner energy are currently underway and the Government of Nunavut is looking for funding for a territorial energy transition that is long overdue" (OpenCanada, 2016, p. 1). The federal government has since announced a $10.7 million budget to INAC over two years to implement renewable energy projects in off-grid Indigenous and northern communities, specifically.

2.4 Social Considerations

2.4.1 Social Assistance and Unemployment

The Nunavummiut are faced with several social obstacles that create a lower than average standard of living for its people. Housing shortages are widespread, and most of the homes in the territory are owned and managed by the Nunavut Housing Corporation. For those living in social housing, there appears to be no incentive to encourage energy efficiency and conservation behaviour. Nunavut is also challenged by unemployment that is twice the national rate, and social assistance is needed for everyday survival. Territorial statistics form 2013 indicate that 41% of the population received some form of social assistance. This type of dependency conflicts with the strong sense of values, resilience, and resourcefulness that have endured with the Nunavummiut for centuries. Today, the lack of education, skills and mobility continues to unravel the social and economic fabric of the territory. It has been suggested that "the territorial government must address the wide gap between job requirements and available skills and, if necessary, encourage employment mobility" (Government of Canada, 2015, p. 42).

2.4.2 Health Effects of Diesel Usage

In 2016, Health Canada published a report titled "Human Health Risk Assessment for Diesel Exhaust" (Health Canada, 2018). The newly published study concluded that diesel exhaust is carcinogenic in humans and is specifically associated with the development of lung cancer. A limited number of studies have investigated other cancers in association with exposure, but the evidence is inadequate to draw conclusions regarding causality. Overall, these conclusions are consistent with the categorization of diesel exhaust as a human carcinogen (Group 1) by the International Agency for Research on Cancer. Regarding non-cancer health effects and the potential causal role of diesel emissions in their development, a number of conclusions have been drawn. The evidence supports a causal relationship between acute exposure at relatively high concentrations and effects on the respiratory system, including increases in airway resistance and respiratory inflammation. The evidence reviewed suggests a relationship between exposure and: 1) adverse cardiovascular outcomes; 2) adverse reproductive and developmental effects and; 3) central nervous system effects. In general, it has been shown that sensitive subpopulations, such as the elderly, children, and asthmatics, can be at greater risk of adverse respiratory effects due to diesel emission exposure. Exposure of the elderly and asthmatics has been shown to increase respiratory inflammation, and exposure in children has been implicated in potential asthma development later in life. Overall, it is concluded that diesel exhaust is associated with significant health impacts in Canada and efforts should continue to further reduce emissions of and human exposure (Health Canada, 2018). While reducing emissions in rural Arctic regions may not have a profound effect on human health as say reducing emission in urban centers would, an initiative to do so would help set community health and environment standards and contribute to overall better practices.

2.4.3 Traditional Attitudes and Renewable Energy

Access to clean energy is only one of many challenges facing Indigenous people. At the 2017 Renewables in Remote Communities Conference hosted by the Pembina Institute, Indigenous leaders spoke of the struggles in their communities. Organizations working to encourage renewable energy projects in communities were told to recognize the realities facing these communities, and ensure projects are consistent with the overarching objectives of healthy community development.

Topics such as cultural reconciliation and decolonization are becoming more mainstream in conversations and media coverage across Canada. Reconciliation involves acknowledging the colonial settler history of Canada and working to build stronger, more positive relationships between Indigenous and non-Indigenous Canadians. Decolonization is about acknowledging the western institutional systems that were imposed on Indigenous people, and empowering Indigenous people to regain control of the institutions and decision-making processes that control their everyday lives. More Canadians are beginning to recognize the need for reconciliation and decolonization. The federal government has recently made encouraging steps by initiating a review of federal laws, policies, and practices to identify and remedy those that are not consistent with Canadian equality principles. Community-led renewable energy projects are one small but vitally important link to remedying this. Of the 36,000 people across Nunavut that depend on diesel for electricity generation and heating, over 84% are Inuit (Nunavut Tourism, 2018). Renewable energy projects encouraged by northern communities can lessen these health and environmental issues, provide economic opportunities, and harness energy in a way that is more compatible with traditional values of living in harmony with nature. Placing energy generation responsibility solely in the hands of the Nunavummiut, with no dependence on imported diesel, can be seen as a positive step towards reconciliation.

2.4.4 U.N. Sustainable Development Goals and Nunavut

The U.N Sustainable Development Goals (SDGs) are a collection of 17 global goals set by the United Nations in 2015 (Figure 5). The SDGs cover social and economic development issues and act as a framework for achieving global sustainable development. The initiative is a resolution adopted by the General Assembly and has been summed up as a guide to "the future we want". The SDGs started as a non-binding document released as a result of Earth Summit held in Rio in 2012. The following is an excerpt from the vision statement:

> "We, the Heads of State and Government and high-level representatives, having met at Rio de Janeiro, Brazil, from 20 to 22 June 2012, with the full participation of civil society, renew our commitment to sustainable development and to ensuring the promotion of an economically, socially and environmentally sustainable future for our planet and for present and future generations" (United Nations, 2012, p. 1).

In a recent speech to the United Nations General Assembly, Prime Minister Justin Trudeau affirmed that, "the Sustainable Development Goals are as meaningful in Canada as they are everywhere else in the world, and we are committed to implementing them at home while we also work with our international partners to achieve them around the world" (Brookings, 2017, p. 1). Amid Canada's many remarkable societal accomplishments, the country is not yet fully on track for any of the SDGs. Figure 6 shows a study by Brookings focusing on 73 of 241 SDG indicators, the results indicate:

- 17 are on track, meaning on course for the SDG target.
- 12 need acceleration, meaning they are currently on course to cover at least half the distance to the target but not yet the whole way.
- 26 need a breakthrough, meaning they are currently on course to cover less than half the distance to the target.

- 18 are moving backwards.

There is major disconnect when observing SDGs in relation to Indigenous groups. Indigenous people throughout the country tend to face the most severe overall disparities, including child poverty, food insecurity, access to medical care, reported violence, and confidence in public institutions.

Climate Action is among the list of UN SDGs that require attention. Even though the distance to reaching the targets are small, the current trajectory is simply not fast enough. Canada still requires a breakthrough in its approach to climate change in order to meet its 2030 emissions targets. In an effort to accomplish this, it would be wise for governing bodies to invest heartily in renewable energy options for Indigenous communities in Canada's north. A restructuring of off-grid diesel generation towards a cleaner energy option would also contribute to other SDGs that are lacking such as: (8) Decent Work and Economic Growth; (9) Industry, Innovation and Infrastructure; (11) Sustainable Communities; and (12) Responsible Consumption and Production. With a trickle-down effect resulting from renewable development, it has been suggested that Nunavut could see an increase in skilled labour training, global awareness, and overall quality of living.

Figure 5: UN Sustainability Goals

(Brookings, 2017)

Figure 6: Summary of Canada's domestic status on SDG indicators

Sustainable Development Goal	Moving backwards	Breakthrough needed	Acceleration needed	On track
1 Poverty		•	•	• • •
2 Hunger & food systems	• • •			
3 Good health & well-being	•	• •	• • • • • •	• • •
4 Quality Education	• •	•		• • •
5 Gender equality	•	• • • • •		
6 Clean water & sanitation	• •	• •	•	
7 Affordable & clean energy	•	•	•	•
8 Decent work & economic growth		• •	•	•
9 Industry, innovation & infrastructure	•	• •		
10 Reduced inequalities	•	•		
11 Sustainable cities & communities	• • •			•
12 Responsible consumption & production		• • •		
13 Climate action		•		
14 Life below water	•		•	• •
15 Life on land		• • •		•
16 Peace, justice & strong institutions	• •	• •	•	• •
	18	26	12	17

(Brookings, 2017)

Chapter 3: Methodology

3.1 Solar Potential in the Study Area

Solar photovoltaic systems have been recently been growing in popularity. Solar cells were first used in a prominent application when they were proposed and flown on a U.S. satellite in 1958, as an alternative power source to the primary battery power source. By adding cells to the outside of the body, the mission time could be extended with no major changes to the spacecraft or its power systems. Research into solar power for terrestrial applications became prominent in the 1960's with the U.S. National Science Foundation's Advanced Solar Energy Research and Development Division (National Science Foundation, 2018). Following the 1973 oil crisis, oil companies used their higher profits to start solar firms, and were for decades the largest producers. Exxon, ARCO, Shell, Amoco, and Mobil all had major solar divisions during the 1970's and 1980's. Technology companies also participated, including General Electric, Motorola, IBM, Tyco and RCA (Reed Business Information, 1979). As costs began to decline during the 1980's and 1990's more terrestrial installations came online, and with subsequent improvements in efficiency the solar industry began to take-off. Recently, there has been tremendous advancements in efficiency and material reductions, with purchase prices as low as $0.50 per watt per panel.

The first solar installation in Nunavut was built in 1995 when Arctic College installed solar panels on its main building in Iqaluit. The install is a 3.2 kW system producing 200 kWh of electricity annually, enough to power one classroom for a year. Despite being over two decades old, most of the 60 panels are still active and working at about 70-75% capacity (CBC, 2015). These panels are mounted on a vertical surface that isn't optimal for solar collection, but does minimize losses due to snow collection (Figure 7). The array is estimated to have efficiencies ranging from 7-11%, depending on the time of year and sunlight conditions (Poissant, Y., Thevenard, D. & Turcotte, D., 2004). There have not been any large-scale PV systems installed in Nunavut, although several projects are currently being assessed.

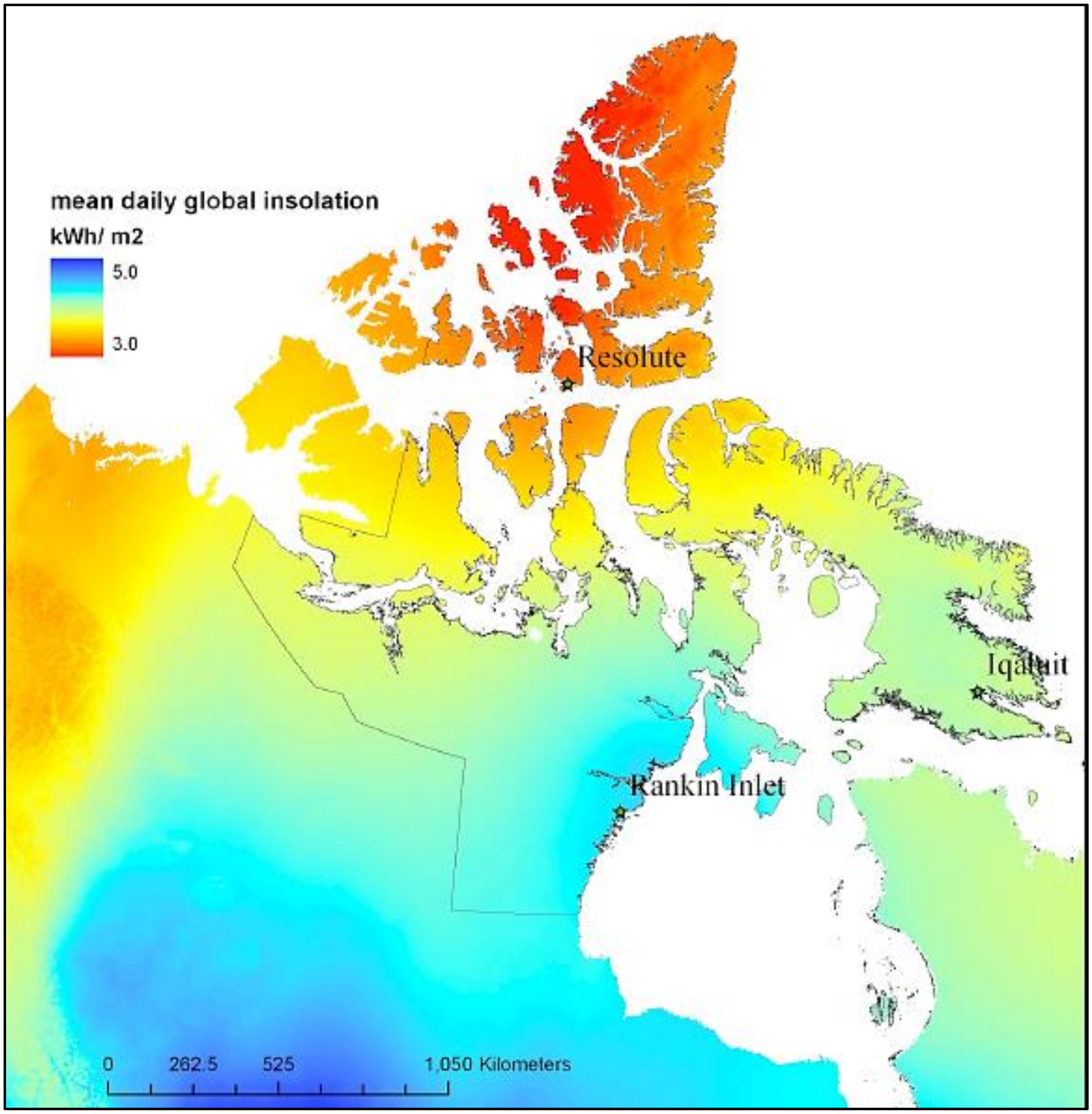
Figure 7: Solar PV Array vertically oriented on Arctic College in Iqaluit, Nunavut

(CBC, 2015)

3.1.2 Solar Mapping in the Study Area

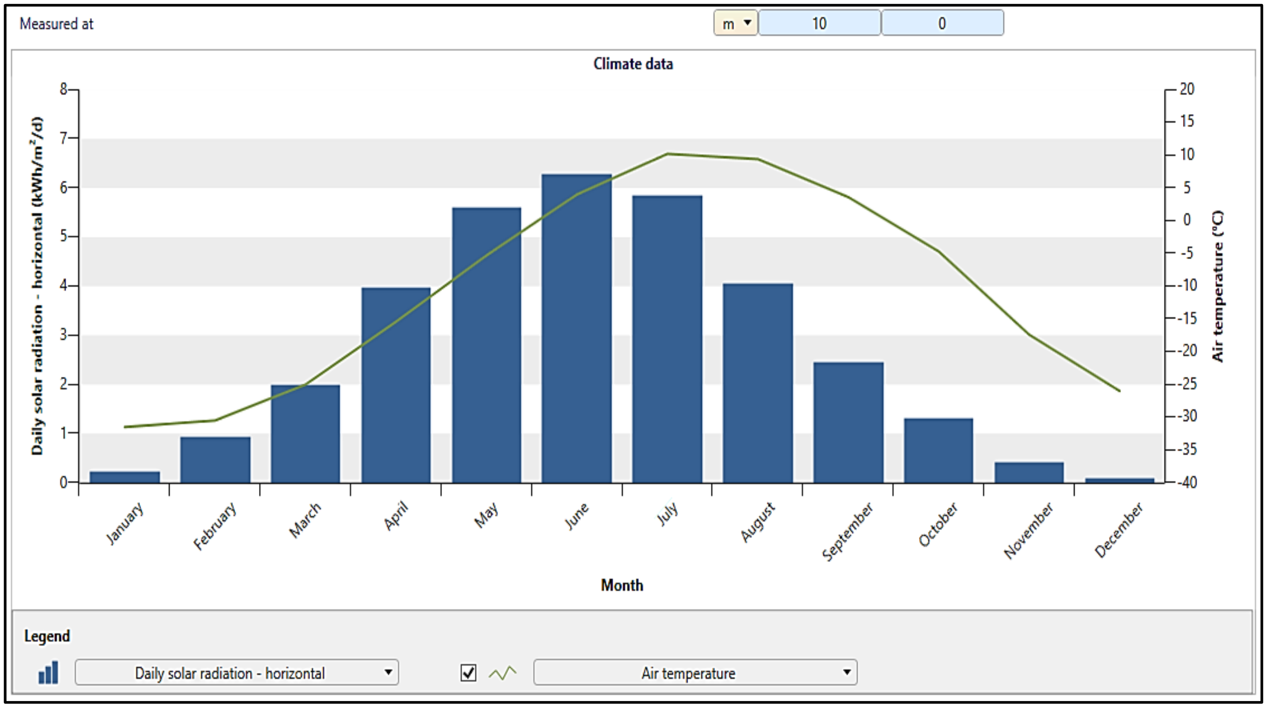
To determine the viability of a solar installation near Rankin Inlet a renewable energy simulation was conducted with RETScreen software. RETScreen is a free numerical simulation program developed by NRCan whereby it is possible to determine the solar exposure and potential energy productions for a given geographic area. The RETScreen simulation was designed to the specific power needs for the study area. Datasets used in RETScreen are provided by NASA and includes climatic variables such as daily horizontal solar radiation, and mean temperatures that were recorded from 1983-2005 (Figures 8 & 9).

Figure 8: Map of Solar Exposure for Nunavut and Study Area



(NRCan, 2018b)

Figure 9: Daily Solar Radiation for Rankin Inlet



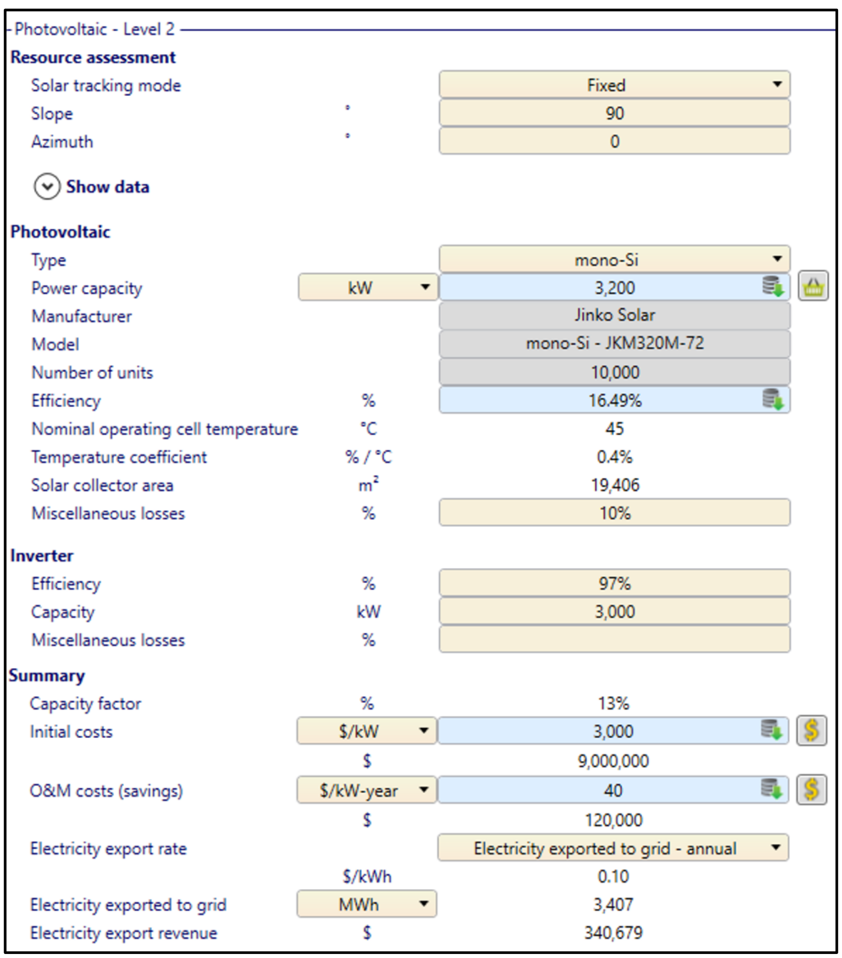
(Adapted from RETScreen, 2018)

3.1.2 PV Simulation Variables for the Study Area

When determining simulation variables for RETScreen entry, the harsh Arctic environment should be considered. Therefore, it is important to simulate using robust PV modules, therefore, Jinko mono-Si JKM320 with a 16.49% efficiency were used. The azimuth for the simulation was set at 0° and facing directly south. The tilt of the panels corresponds to the angle of orientation relative to the flat ground surface. The optimal angle for the study area is high due to the 62.8° latitude of the study area resulting in a low solar pathway relative to the horizon. Because of the latitude and of the possibility of snow interference, this simulation used a 90° tilt similar to that being utilized at Arctic College in Iqaluit. Energy losses occur in most PV systems due to substances like dirt and snow covering the cells. For the purpose of this study the losses were set to 10% based on losses occurred at the install at Arctic College. These systems are equipped with an inverter that converts DC power produced by the system to AC power required by the grid. Efficiency of modern inverters is approximately 97%. Inverter capacity refers to the nominal output of the system in kW AC, and is determined based on the size and capacity of the overall system. Because there is an excessive amount of open space on the tundra near Rankin Inlet, An optimal PV spacing design is consider that results in no array losses or shading of any panels as a result of interference.

After the values were entered for the RETScreen simulation a 13% capacity factor was determined for the array (Figure 10). The PV system for the simulation contain 10000 panels with an installed capacity of 3.2 MW and a 3.0 MW_{ac}.

Figure 10: PV Plant Input Parameters for RETScreen Simulation



Photovoltaic - Level 2		
Resource assessment		
Solar tracking mode		Fixed
Slope	°	90
Azimuth	°	0
Show data		
Photovoltaic		
Type		mono-Si
Power capacity	kW	3,200
Manufacturer		Jinko Solar
Model		mono-Si - JKM320M-72
Number of units		10,000
Efficiency	%	16.49%
Nominal operating cell temperature	°C	45
Temperature coefficient	% / °C	0.4%
Solar collector area	m²	19,406
Miscellaneous losses	%	10%
Inverter		
Efficiency	%	97%
Capacity	kW	3,000
Miscellaneous losses	%	
Summary		
Capacity factor	%	13%
Initial costs	$/kW	3,000
	$	9,000,000
O&M costs (savings)	$/kW-year	40
	$	120,000
Electricity export rate		Electricity exported to grid - annual
	$/kWh	0.10
Electricity exported to grid	MWh	3,407
Electricity export revenue	$	340,679

(Adapted from RETScreen, 2018)

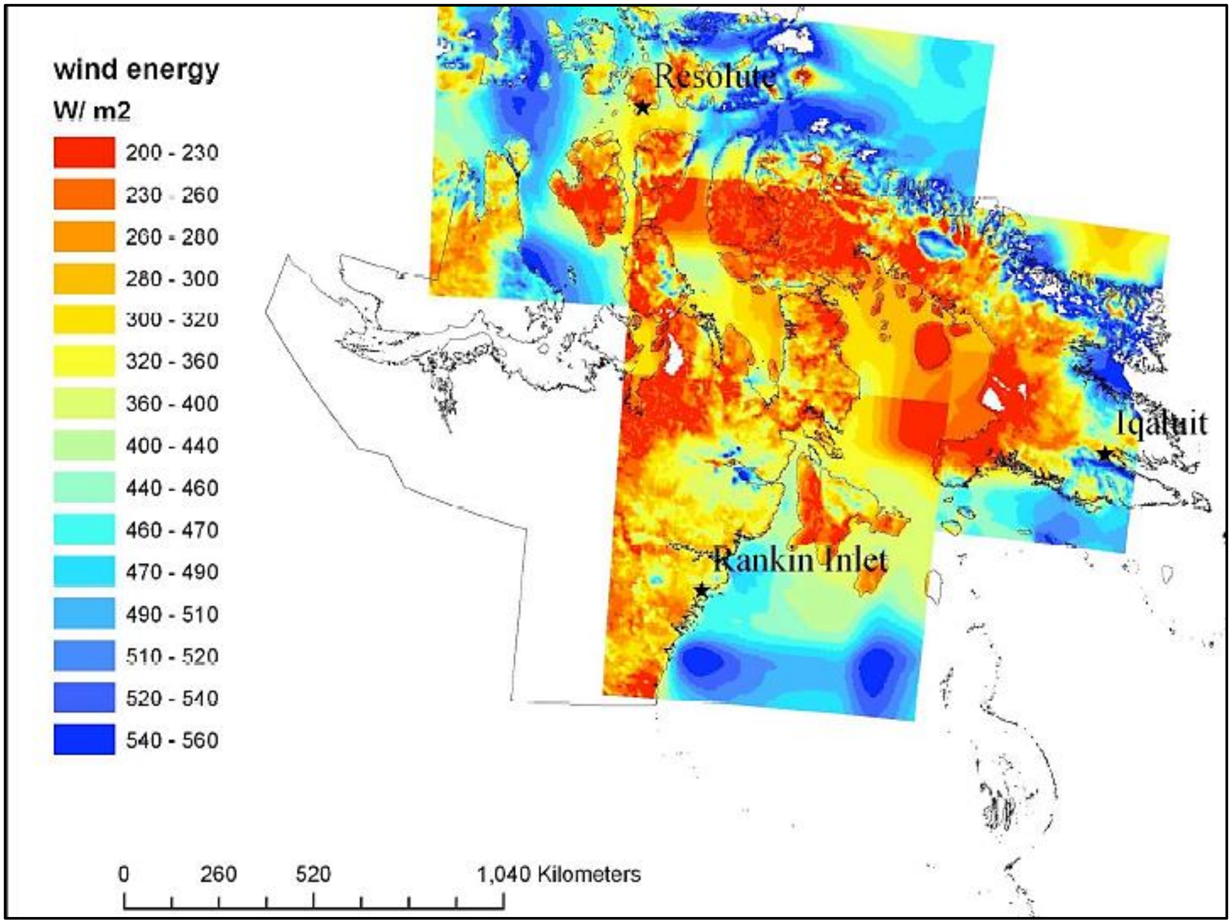
3.2 Wind Potential in the Study Area

As mentioned in Chapter 2, Rankin Inlet has long been considered a viable location for wind energy development and has some of the highest energy capturing potential in the territory (Figure 11). This is, in large part, due to the favorable conditions that exhibit consistently high wind velocities combined with low wind shear. Wind shear refers to the variation of wind over either horizontal or vertical distances. Ideal wind development locations are those with low wind variation that allow for optimal turbine orientation. In general, the wind shear coefficient for a smooth terrain will be much lower compared to that of a rugged area has geographic obstacles. For example, the town of Iqaluit is located along the sheltered shore of Frobisher Bay, surrounded by large hills and rocky fjord-like cliffs. These physical condition result in a wind shear coefficient value of about 0.25. In contrast, the town of Rankin Inlet is located on a flat area with few obstacles that support a coefficient value of 0.15 (Government of Canada, 2004). Consistently high winds and low wind shear make the study area an attractive target for potential resource development.

3.2.1 Wind Mapping in the Study Area

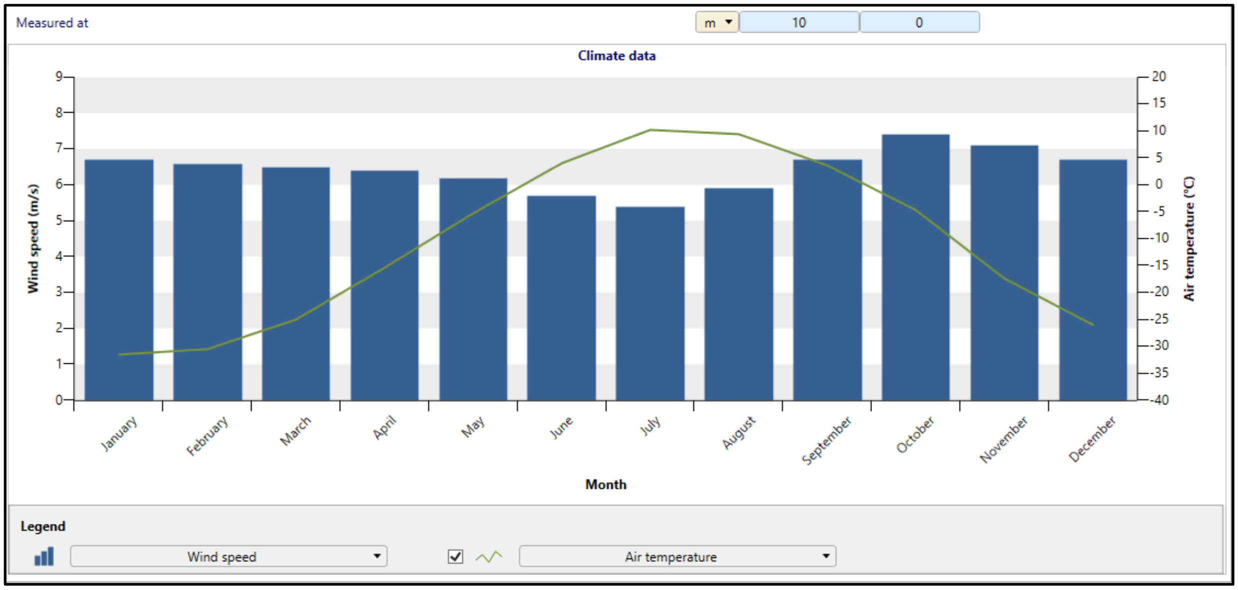
The Canadian Wind Atlas is the essential tool for all primary wind resource data extraction in the country. This data is provided by the Government of Canada and is free of charge. The data was originally produced by running the statistical-dynamical downscaling method. This method involves the following steps: 1) wind climate classification; 2) mesoscale simulations; 3) statistical post-processing and; 4) microscale modelling (Canadian Wind Energy Atlas, 2003). Figures 11 and 12 show wind energy measured in W/m^2 and wind speed measured in m/s for Nunavut and the study area.

Figure 11: Wind Map of Nunavut and Study area



(Adapted from Government of Canada, 2018b)

Figure 12: Monthly Average Wind Speeds for Rankin Inlet



(Adapted from RETScreen, 2018)

3.2.2 Wind Simulation Variables for the Study Area

For the purpose of the simulation, the study uses TUGLIQ Energy's turbine installation at Raglan Mine as the best example of a wind installation currently operating in a climate similar to that of Rankin Inlet. In 2014, the TUGLIQ project deployed an Arctic-rated 3 MW wind turbine generator to aid in powering mine operations (Figure 13). The developers took a thoughtful approach and considered various aspects of the Arctic environment in the design process. For example, a spider-like steel foundation was engineered for the turbine in order to alleviate potential problems associated with melting permafrost, should global warming accelerate over the 20-year life cycle of the turbine. The foundation extends structural support well below the permafrost active layer, and elevates the foot of the turbine one meter above ground. "Also, a microgrid controller was installed that monitors demand for wind power and variations in supply, and economically dispatches the charge and discharge of the energy storage units, through complex algorithms, to produce a smooth power output that enables high (50%) wind power penetration. The setup successfully rode-through wind power dips and drops without tripping the security mechanisms of the Raglan diesel micro-grid. The turbine achieved 97.3% availability since its installation in 2014, displacing 3.4 million liters of diesel and 9,110 tonnes of greenhouse gases over 18 months" (NRCan, 2016).

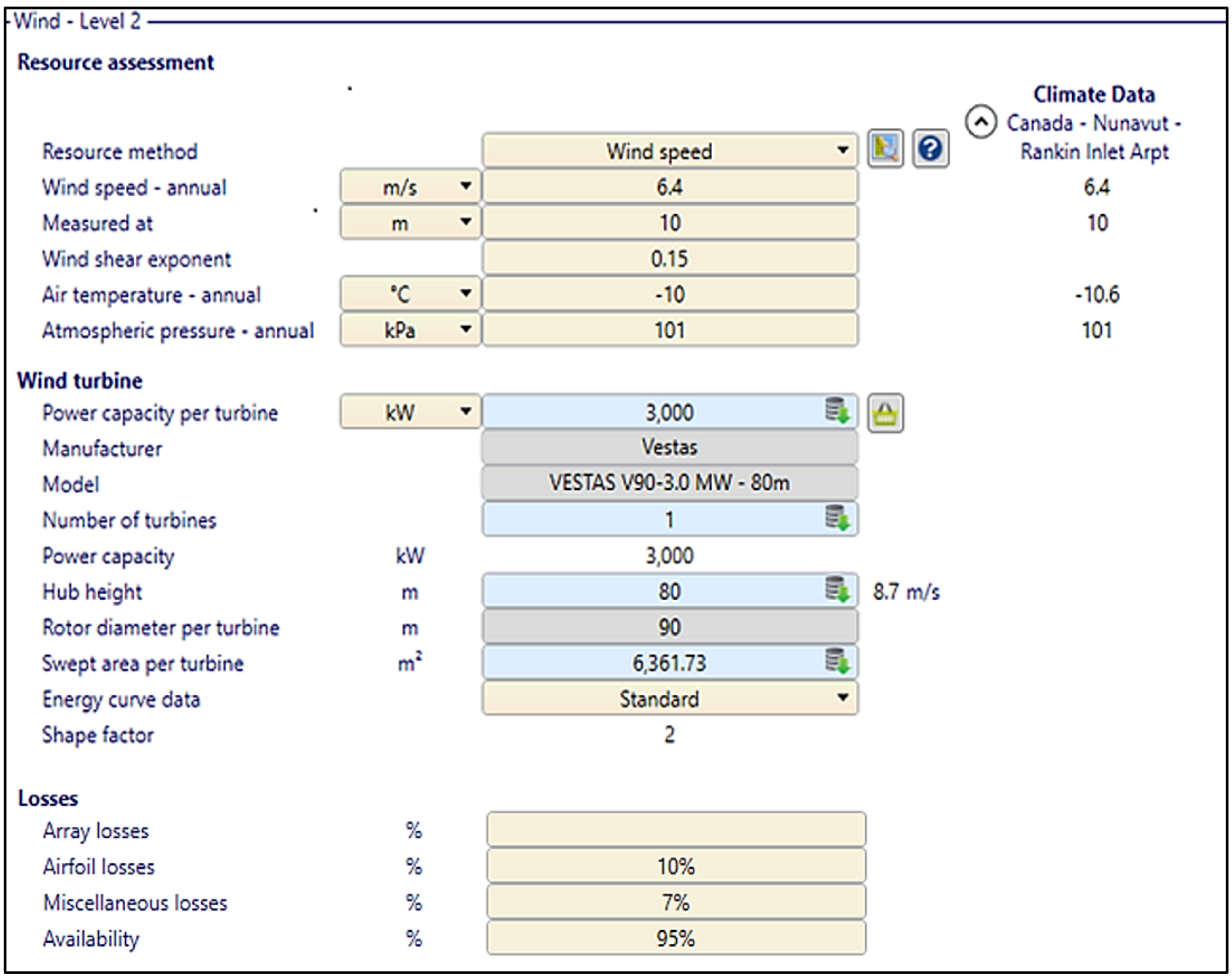
Similar to PV simulations, energy loss variables also need to be considered when designing a wind project simulation. Airfoil losses are also a common loss incurred by a build-up of unwanted materials on turbine blades, most often insects or ice. Energy losses that occur as a result usually rage from 0-10%. For a cold area such as Rankin Inlet, losses as a result of ice build-up are likely to be an ongoing issue. However, wind turbine manufacturers are increasingly recognizing the impacts of cold climate operation and are building turbines better equipped to handle winter conditions. With the installation of "cold weather packages" which provide heating to turbine components such as the gearbox, motors, and battery, some turbines can operate in temperatures down to -30°C. Various types of rotor blade de-icing and anti-icing mechanisms, such as heating and water-resistant coatings are being employed by projects throughout the world, and there are operational strategies to limit ice accumulation.

Figure 13: TUGLIQ's wind turbine at Raglan Mine

(NRCan, 2016)

Mechanical losses occur in wind turbine systems that also need to be taken into consideration. Moving parts such as the gearbox and ball bearings have a friction coefficient that has to be considered when calculating the capacity factor for wind energy installations. The value for this simulation will be 2% mechanic loss. Miscellaneous losses can also occur in the form of cut-outs due to extreme cold, therefore, a factor of 5% was entered in anticipation of probable temperature drops. Scheduled maintenance must also be accounted for, and because of the extreme climate conditions in the study area, these losses will likely be higher than average. For the purpose of this study a value of 95% system availability will be considered (Figure 14).

Figure 14: Wind Turbine Input Parameters for RETScreen Simulation



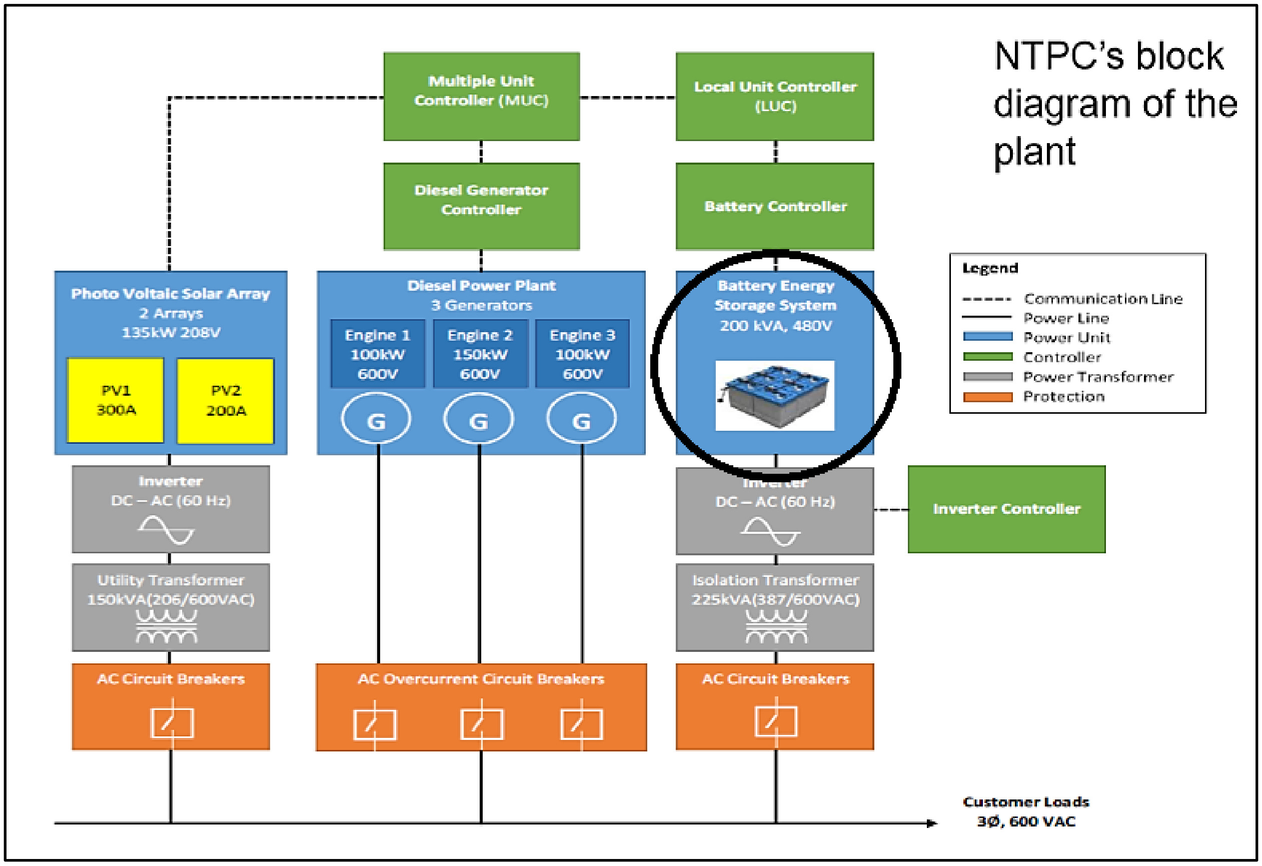
(Adapted from RETScreen, 2018)

3.3 Incorporating Battery Storage into the Mix and System Costs

Energy storage options, although expensive, are essential to incorporating renewable energy projects in the Arctic. The two project examples that have been referenced throughout this study, Colville Lake and Raglan Mine, both have battery storage that is key to maximizing energy capture and minimizing wastage. Colville Lake has a 200 kWh battery install (Figure 15) being fed by a 130 kW solar array. When the battery is 100% charged the grid will switch over to battery power and the town will be powered by solar power until battery power levels reach 40%, then the diesel generators switch back on.

Raglan Mine has a 200 kW, 250 kWh Li-Ion battery for transition backup that supplies start-up power to the generators when switching from wind power to diesel. The system also has a 200 kW/1 MWh system hydrogen electrolyser rated at 315 kW coupled to 198 kW hydrogen fuel cell. The hydrogen fuel system is powered by wind energy and produced hydrogen from water. The Raglan Mine system costs $19 million for 3 MW production (NRCan, 2016).

Figure 15: Colville Lake PV-diesel hybrid system schematic



(NTPC, 2017)

3.4 Interview with Rankin Inlet Residents about Renewable Energy

To fulfill the social pillar of this study, and to acquire pertinent information regarding the attitudes surrounding renewable energy, interviews were conducted that help gain insight into the community values of the residents of Rankin Inlet. Community members that lived in Rankin Inlet for more than 3 years were considered permanent residents. This survey utilized qualitative open-ended questions to explore the various perspectives of both Inuit people and non-Indigenous residents. Perspectives regarding the acceptability of renewable energy are important when assembling a holistic sustainability study.

Prior to beginning the survey process, ethics guidelines were examined based on the University of Calgary Ethics Document for SEDV 625 students and the Interview Code of Conduct. Due to time constrains and the logistical issues with posting consent forms, cold call telephone interviews were conducted at random to 73 households, of whom 15 cooperated fully with the objectives and questions of the survey. The remaining 58 households did not agree to answering questions from the survey. Although the results of the survey provide insight into what many residents perceive with regard to renewable energy, it should be noted that this is a very small sample of Rankin Inlet residents. A pre-determined set of questions was used for the survey and most surveys were 10-15 minutes in duration (Appendix A). Questions were framed in such a way that the surveys would generate opinions on: (1) perceived impacts of diesel generation; (2) perspectives on renewable energy and; (3) perceived factors hindering renewable energy expansion.

Chapter 4: Analysis, Findings, and Interpretations

4.1 Incorporating Renewable Energy Technologies in Rankin Inlet

The following is a review of the results and findings of the RETScreen simulations described in Chapter 3. With the aid of the simulations, it is evident that substantial economic and environmental benefits can result by incorporating renewable energy projects that subsequently reduce the amount of diesel fuel consumption. Also, through observing other projects in the Arctic it has been made evident that renewable energy technologies are operationally viable in Rankin Inlet. Determining whether they are economically viable requires a comparison of costs to the current system. Furthermore, It should be noted that to provide an accurate and realistic economic assessment it is essential to take into consideration the potential for project funding through the numerous (and complex) government subsidies that exist for electricity use and generation in Nunavut.

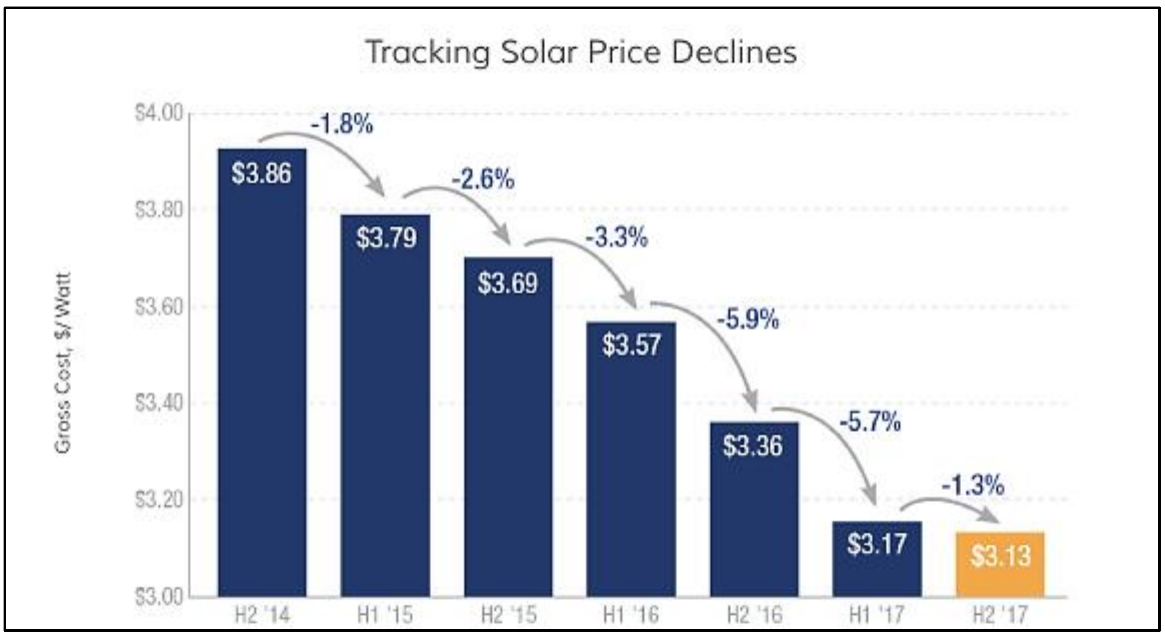
4.1.1 Current Diesel System in Rankin Inlet

The Rankin Inlet diesel off-grid system currently consists of five generators that produce about 17,400 MWh annually (Government of Nunavut, 2016a). Electricity costs total $8.1 million a year and emits 13,598 tonnes of CO_{2eq}. As each liter of diesel emits 2.785 kg of CO_{2eq} simple division concludes that approximately 4.88 million liters of diesel fuel is consumed for electricity generation only. The present system operates year round at approximately 99% efficiency. Other cost associated with transportation of diesel exceeds the actual cost of the fuel and will not be considered for this comparison due to the complexity of the diesel transportation industry in Nunavut.

4.1.2 PV Potential of the Study Area

For the PV system, it was determined that the installed capacity would be 3.2 MW supplying approximately 3,659 kWh annually to the town. The amount of annual GHG emissions displacement for such a project totals 2,855 tonnes of CO_{2eq}. The particular array design was projected in RETScreen to cost $9 million to install, a value based on solar panel prices from 2016 which does not consider the costs of material shipping and labour. For that reason, recent cost modifications need to be considered when estimating a current project budget. Firstly, solar panel prices have steadily been declining in recent years, and since 2016 panel costs have decreased by roughly 15% (Figure 16). Secondly, it was advised by the software demonstrator to mention, but not quantify, the costs of road building and cradle mounting on permafrost (Ross, *person communication*). In summary, the total cost is an estimated $10 million for 3.2 MW PV power plant with a 13% capacity factor.

Figure 16: Decreasing Costs of Solar Panels



(EnergySage, 2018)

4.1.3 Wind Energy Potential of the Study Area

For the wind simulation, it was determined that the installed capacity would be 3 MW supplying approximately 9,733 kWh to the town. Proportionately, the amount of annual GHG emissions displacement for such a project totals 7,614 tonnes of CO_{2eq}. The cost of installing the selected turbine is roughly $3 million per installed MW (TransAlta, *personal communication*) but several other budgetary factors must be considered. Similar to the TUGLIQ project at Raglan Mine, the install would include a reinforced base for potential permafrost issues, as well as a cold weather package that heats the turbine lubricant when temperatures reach -30°C between the months of November and March. In summary, the total cost is an estimated $10 million for a 3.0 MW installed capacity turbine with a 37% capacity factor. A comparison of the current diesel system with RETScreen simulated PV and wind turbine power plants can be seen in table 4-1.

Table 4-1: Comparison of Current Rankin Inlet Electricity Generating System and Proposed Renewable Energy Systems

Variables	**Diesel System**	**Solar PV System (potential)**	**Wind System (potential)**
Annual kWh	17,396,062	3,407,000	9,733,000
% kWh	100	19.6	56
Diesel Fuel (litres)	4,880,000	956,480 equivalent	2,733,931 equivalent
Economics ($)	8,108,206 (annually)	10,000,000 (one-time)	10,000,000 (one-time)
GHG (tonnes CO_{2eq})	13,598	2,664 displaced	7,614 displaced

(Byrne, 2018)

4.1.4 Battery Usage and Costs

Storage options should be implemented in the proposed projects in order to maximize energy usage and minimize energy dumping. Similar to the TUGLIQ Glencore project, a Lithium-ion stationary battery would be best applied to the aforementioned power plants. Figure 17 illustrates how lithium-ion batteries are about a third of the weight and half of the volume when compared to lead-acid (flooded, AGM, and gel) thus making them better for shipping to northern locations. "Lithium-ion batteries are in a league of their own when compared to all other battery types since they are significantly more energy dense. We are at the transition between lead-acid batteries, the tried-and-true technology used for decades, and lithium-ion's promise of higher density, improved resiliency, and longer cycle life." (Medium, 2017, p. 1).

The Lithium ion battery system at TUGLIQ Glencore is a 200kW/250 kWh unit that can accept and store energy from all sources including diesel generators, solar and wind. It is designed for remote communities and mines, which are off-grid and powered by diesel (Electrovaya, 2015). The total cost of the battery was $0.7 million. It is estimated that 3 to 5 of these batteries would be required for the proposed solar and wind projects.

Figure 17: Battery Technology Comparison

	Flooded lead acid	VRLA lead acid	Lithium-ion (LiNCM)
Energy Density (Wh/L)	80	100	250
Specific Energy (Wh/kg)	30	40	150
Regular Maintenance	Yes	No	No
Initial Cost ($/kWh)	65	120	600
Cycle Life	1,200 @ 50%	1,000 @ 50% DoD	1,900 @ 80% DoD
Typical state of charge window	50%	50%	80%
Temperature sensitivity	Degrades significantly above 25°C	Degrades significantly above 25°C	Degrades significantly above 45°C
Efficiency	100% @20-hr rate 80% @4-hr rate 60% @1-hr rate	100% @20-hr rate 80% @4-hr rate 60% @1-hr rate	100% @20-hr rate 99% @4-hr rate 92% @1-hr rate
Voltage increments	2 V	2 V	3.7 V

(AllCell, 2012)

4.2 Financial Analysis

Several factors have to be taken into consideration in order to perform a suitable financial analysis for of project of this size and location. While renewable energy projects in more populous and accessible areas have a relatively straightforward method to determine capital expenditures and budget estimates, equivalent projects in the Arctic require consideration of many case specific factors. Nonetheless, an analysis of Internal Rate of Return (IRR) and Payback Period are two very important metrics that allow stakeholders to understand the value of renewable investments. Appendix B outlines the expenses and cash flow quantifications that determine these metrics for both projects.

The PV + battery proposal was determined to provide 8.35% rate of return with a 9.6 year payback. It should be mentioned that a loan discount rate is not considered due to the fact that all electricity generation in Nunavut is controlled by the territorial government. Because of this, it is likely that the future of Nunavut electricity generation will not be developed by private investment and the government will continue to incur all costs without the need for loans.

The wind + battery proposal was determined to have a much higher IRR and shorter payback. A 3.35 year breakeven period was determined based on a 29.53% rate of return. The high rate of return is very much influenced by the current rate of electricity in Rankin Inlet being $0.49/kWh, combined with the high wind resource availability values that RETScreen uses in its simulations. As the turbine produces over 2.5 times more electricity than the PV array, its contribution to cash flow is considerably higher.

Factors that may create variance in the financial value of these projects can be difficult to quantify. For instance, a decrease the IRR values for both proposed projects may be caused by operational downtime due to unpredictable extreme cold or icy weather characteristic of the study area. Conversely, an increase in the value could result from rising fuel prices, the cost of environmental cleanup of spills, and diesel generator malfunctions. Due to this unpredictable nature, the annual cash flow values in Appendix B were kept consistent throughout the 20 year lifespan of the project and only operations and maintenance expenditures were considered.

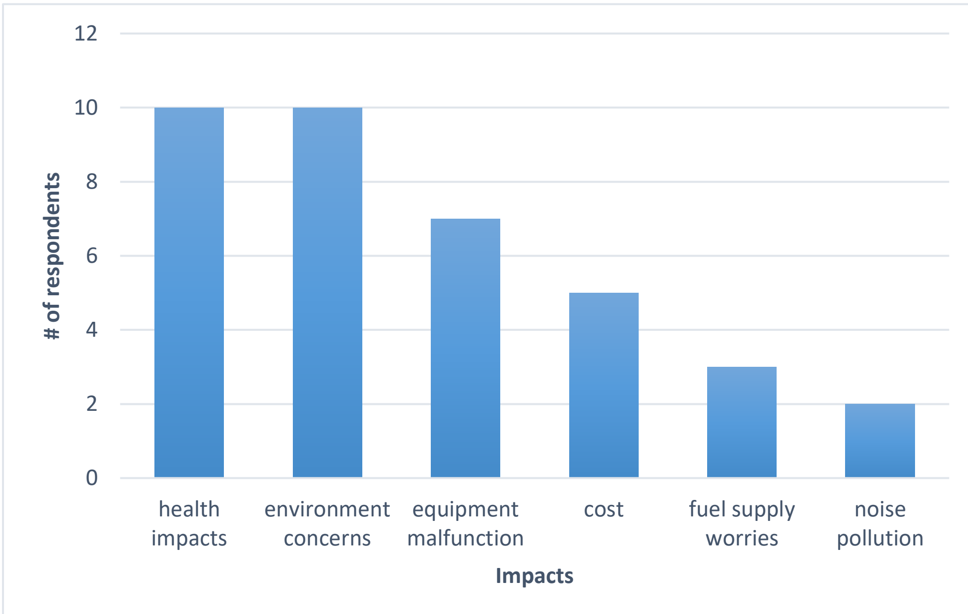
4.3 Public Perspectives

4.3.1 Perspectives on the Current Energy System in Rankin Inlet

During the survey process, a number of ideas were discussed with the respondents that touched on the attitudes and opinions of Rankin Inlet residents. The main topics of discussion were related to diesel consumption and renewable energy incorporation. The results of this survey are important for understanding the quality of living with respect to energy consumption, reliability of their current power system, and the perceived effects of incorporating renewable energy.

To understand the potential effects that respondents believe renewable energy may have on their community, it is important to explore the perceived impact of diesel use. Respondents were asked about their knowledge of the electricity power plant in Rankin Inlet and what they perceived were impacts resulting from it. The participants acknowledged the following: 1) health impacts; 2) environmental impacts; 3) noise pollution; 4) cost; 5) equipment malfunctions and; 6) worry about fuel supply. Figure 18 shows the distribution of concern.

Figure 18: Perceived Impacts of Diesel Generation



(Byrne, 2018)

With the results of the survey it is clear that health and environment are the main concerns. Some residents were worried that diesel emissions are leading to increased lung diseases and other residents felt that just knowing that large volumes of diesel was being burned made them feel unwell. The sight of exhaust was another factor that created displeasure in one of the respondents. Other residents expressed concern for diesel spills on land and/or at sea.

Equipment malfunction was the third most considered impact. Some residents were quick to point out the malfunction of the main diesel generator and auxiliary generator that happened back in 2008. "The problem began Feb. 18 when one of two main diesel generators supplying power to 2,300 Rankin Inlet residents mysteriously shut down. The other main unit went down Tuesday and one of the auxiliary generators went off line the day after. By Wednesday's end, a town that normally has a peak demand of 2,700 kilowatts had less than half that on tap" (CTV, 2008, p. 1).

Other frequent perceived impacts that respondents discussed during the survey were based on the negative economic impact that diesel use had in the community. The amount that residents were being charged on electricity bills was a general concern and the constant threat of increasing rates was worrisome. Some residents expressed concern over diesel fuel supply. One resident stated that "there's always the possibility that we will run out of fuel, then what? Do we all freeze?" Noise pollution was the least concern and those who stated that they had an issue with noise were among the ones living closest to the power plant.

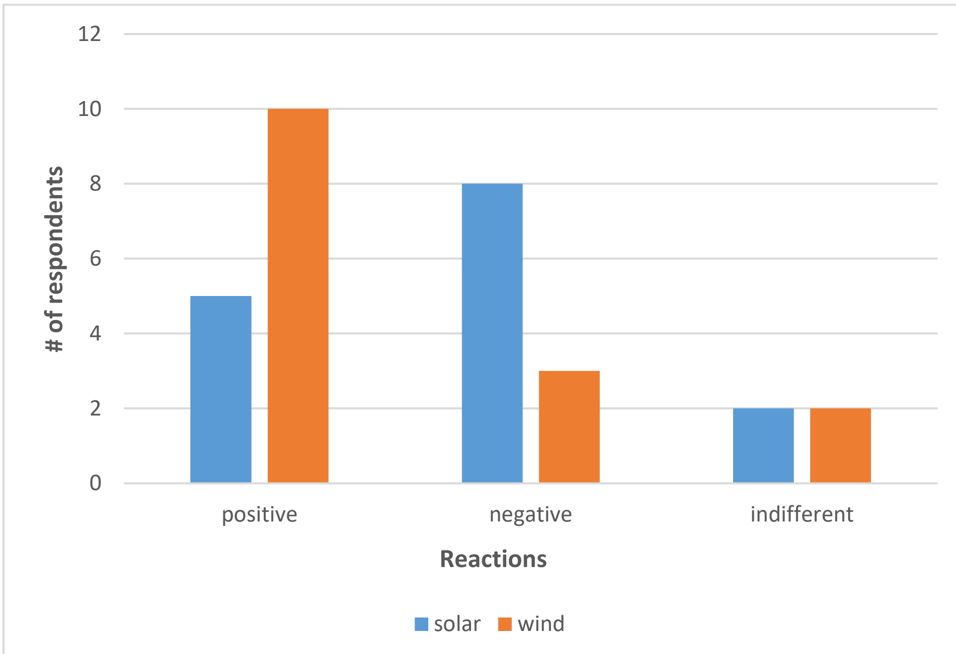
Understanding the perceived impacts is important for several reasons. If data is collected regarding public concerns, then these concerns can be addressed. Addressing the concerns will likely result in the initiation of a plan that involves educating the public on the true environmental, health, and cost effects of maintaining the current system. It is important to mitigate the concerns that the residents of Rankin Inlet have with their current system because sustainable development requires approval in the form of a social license from community members. Once education and social license are in place, and there's a genuine desire for a change in energy infrastructure for the community, the policy makers and politicians will have to take notice.

4.3.2 Perspectives on Renewable Energy in Rankin Inlet

During the survey, respondents were asked about their opinion on renewable energy as a source of electricity for Rankin Inlet. Figure 19 shows the results of the survey questions that can be divided into three categories: 1) positive opinions; 2) negative opinions and; 3) indifference. Both solar and wind power were the main focus here and, although conversations occasionally mentioned other renewable energy technologies, there was no data collected on any of other renewables. For example, some respondents briefly mentioned the possibility of hydroelectricity being supplied from Manitoba, a subject previously mention in Chapter 2 of this study.

Survey results show a preference for wind power over solar, while some respondents were indifferent to both renewable energy options and did not state any positive, or negative, perspectives of either. The results of the survey are discussed in further detail below.

Figure 19: Opinions on Renewable Energy Incorporation



(Byrne, 2018)

<u>Solar Energy</u>

During the survey process, eight respondents felt that solar power was not useful in Rankin Inlet as a substitute, or hybrid supplement, for the current diesel generator. A total of five respondents felt that solar would be a good idea. The conversations focused on both large scale solar assemblies with brief mention of small-scale home installations. Of the negative respondents, most stated that the long winters and snow would be an issue, and one resident was concerned about theft. Of the positive respondents, most agreed that home installation of PV modules was the best option to counter the cost of electricity bills and the concept of a large-scale solar power plant that combined with the diesel generator seemed possible. The positive respondents who supported solar felt that it should be tested for the summer months to take advantage of the long daylight hours experienced in Rankin Inlet.

Wind Energy

The idea of developing wind energy was much more receptive among those surveyed. This is likely due to the fact that there has been a small wind turbine in Rankin Inlet since the early 2000's. Ten respondents expressed positive opinions about installing a larger wind turbine while three respondents expressed negative feelings towards the turbine. Perspectives on wind energy were shaped by the knowledge that locals had about wind availability. Some respondents stated that the relatively constant windy conditions were ideal way of helping to power the town. One skeptical respondent stated that he was uncertain if the cold weather and snow would affect the operation of large turbine. Doubt was also expressed due to the fact that the current turbine is often broken and not functioning properly.

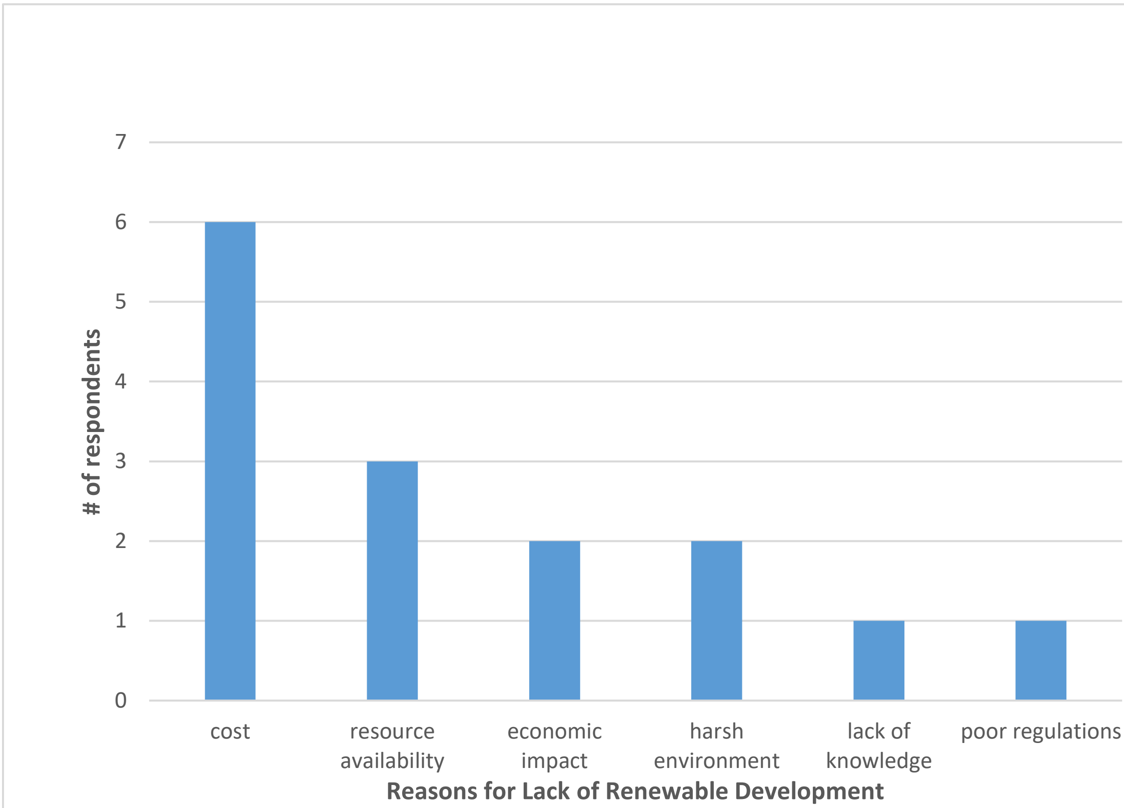
Indifference

The indifferent respondents claimed they had very little knowledge of renewable energy technologies and were more concerned with the current diesel generating system. These two respondents expressed the concern for break downs and malfunctions and referenced the issue that occurred in 2008. One resident felt that the focus must remain on the current system and making sure that it runs efficiently and consistently and that the backup system does not fail when it is required to cut-in.

4.3.3 Perceived Factors Preventing Renewable Energy Installation

Participants of the survey were also asked for reason why they thought renewable energy wasn't more popular in Rankin Inlet, and why the QEC hasn't yet installed wind or solar. The reasons supplied by the survey included: 1) cost; 2) renewable resource availability; 3) economic impact; 4) harsh environment; 5) lack of knowledge and; 6) poor regulations. Figure 20 displays a summary of the opinions respondents gave regarding reasons that renewable energy development is slow to catch on.

Figure 20: Opinions on Why Renewable Energy Hasn't Been Developed



(Byrne, 2018)

The major reason residents gave for lack of renewable energy development was related to the high costs of such projects. Six respondents stated that the price of solar and wind installations is the likely factor preventing renewable infrastructure from being built. One respondent stated that "if we can't afford a new diesel generator then how can we afford new windmills?"

The second reason given for lack of development was associated with renewable resource availability when three respondents expressing concern about whether there was enough wind and sunlight to power the town. One resident stated that "sometimes the wind is too strong and that is a problem".

The economic impact of moving away from diesel was a concern for some. Two respondents felt that not using diesel will hurt local generator operators and fuel distribution facility employees, and renewable energy will therefore result in lost jobs.

The harsh environment was a reason that two respondents gave, stating that the extreme cold, snow, and ice will prevent turbines and PV arrays from working properly. “The fact that there is no proven cold weather technology is preventing it from happening here” claimed one respondent.

Another respondent stated that lack of knowledge about renewable options could be a reason and they felt that information sessions and courses should be offered and provided locally. Misinformation was the main concern, and they felt that lies are being told about the birds and animals that are effected by windmills.

One respondent stated that poor regulations are preventing it from happening and that the lack of support from the government was the major issue. He expressed that “the government thinks a power plant overhaul is too much work”.

Chapter 5: Discussion

As indicated throughout this study, there are a number of challenges associated with developing renewable energy resources in Rankin Inlet, but it is evident that integrating sustainable energy development technologies could provide a number of benefits. The associated benefits identified are primarily diesel fuel savings, emissions reductions, and environmental improvement.

Although the upside is significant, the main factor preventing renewable development is economic feasibility, as the costs of renewable energy installations are perceived as risky and expensive. In order to influence this perception, a thorough understanding of project economics in required. This study helps identify the investment potential of renewable energy technologies and the downstream effect of subsequently reducing diesel fuel consumption. The residents of Rankin Inlet, on average, have a yearly cost of $12,818 per person to maintain the current off-grid diesel electricity and home heating system. The total spent annually for both electricity and home heating is $35,594,000 and over half of that amount is spent on electricity alone (Government of Nunavut, 2016a).

As Chapter 4 outlines, wind and solar installations are technically and economically viable in the study area. Considering that the life of both a PV system and a wind turbine is approximately 20 years, an install of either one of the proposed projects would provide the community with relatively reasonable electricity cost, when compared to the existing system. The current cost of diesel-generated power is 0.49 $/kWh (Table 1-2). However, since electricity subsidies in Nunavut are multi-layered and complex, and considering the potential impact of the federal carbon tax (Nunatsiaq News, 2018), the true cost of electricity is difficult to assess at the time being. As such, with a renewable energy simulated cost as low as 0.07 $/kWh (Table 5-1), it is likely that if the true current cost of electricity were to be calculated, renewable energy would be much more attractive and undeniably convenient for residents of Rankin Inlet.

Table 5-1: Energy Costs

PV Plant Cost	$10,000,000
Battery Cost	3 x $700,000 = $2,100,000
Capital Costs	3,781 $/kW installed, 0.18 $/kWh average for 20 years
Features	20 year lifespan, minimal O&M costs, easily modified
Challenges	13 % capacity factor
Wind Turbine Cost	$10,000,000
Battery Cost	5 x $700,000 = $3,500,000
Capital Costs	4,500 $/kW installed, 0.07 $/kWh average for 20 years
Features	20 year lifespan, 37 % capacity factor, easily modified
Challenges	O&M costs are unpredictable

(Byrne, 2018)

5.2 Technical Feasibility

Based on the results of the RETScreen simulations for both wind and solar, it is fair to conclude that both technologies, if implemented properly, could dramatically change the standard of living for residents. Between the months of March and September, solar power could contribute to more than 19% of the required local electricity. Similar to the Corville Lake hybrid system, a power plant would have to be designed that could store excess energy, eliminate the need to dump electricity, and minimize the diesel generator usage during the spring and summer months.

Wind energy, on the other hand, has the potential to operate year round with minimal availability losses due to climate and weather. Wind, combined with short-term battery storage, has the potential to displace approximately 55% of the current diesel electricity. With the advancement in cold climate wind technologies, like those used at the Raglan Mine, it is realistic to suggest replacing diesel-fuelled generators with a system that harnesses naturally available energy. With an expanded wind development model that includes several turbines and a larger battery station, it is possible to displace more than 100% of the diesel used in the community.

5.3 Barriers Preventing Development

Major barriers exist that prevent the development of both wind and solar in the Rankin Inlet area. The main barrier is involves a lack of accurate resource data. Proper monitoring of both solar and wind resources is required for extended periods of time in order to gain the most precise resource measurements. RETScreen simulations provide solar data from satellite databases that give general insolation values on a region scale. Wind values are the product of observed wind measurements encountered at the local airport and entered into the Canadian Wind Atlas. Neither solar nor wind takes into account specific, and optimal, geographic locations on a fine scale. The QEC is currently monitoring wind conditions in the nearby town of Arviat in order to build an accurate dataset to help determine whether or not a turbine installation is viable there (Government of Nunavut, 2016b). There are no known similar solar monitoring programs in Rankin Inlet at this time. It is suggested that a comprehensive renewable resource portfolio be developed for the study area which should include solar and wind data from ground monitoring stations.

As previously discussed, there are numerous renewable energy technologies that could be technically viable in the study area, these include hydropower and tidal power. However, a major barrier for determining their viability is also due to the lack of available data. In the case of tidal power, there have been very little tidal data gathered in Nunavut. New tidal energy harnessing technologies are combating the issue of ice coverage during winter months and their application to the study area will require such data. Therefore it is suggested that a comprehensive renewable resource portfolio be developed in for the people of Nunavut. The portfolio should include accurate hydrology, solar and wind data collected from ground monitoring stations, as well as tidal data and any other natural resource. This data is vital for energy independence within the territory.

5.4 Community and Social Development

Due of the abundance of natural power, Rankin Inlet is at a major advantage compared to the majority of the rest of Canada. As the QEC and territorial government continues to urge customers to reduce their power consumption, it is clear that creating good habits involving energy awareness is a socio-political objective. As communities get larger, society progresses, and the standard of living increases, so will electricity usage. This progress could be magnified with the development of Rankin Inlet's renewable energy resources. Introducing cutting-edge technology, such as that installed at Raglan Mine, may put the town at the forefront of wind harnessing in northern climates, and the data extracted from such a project may be applied throughout other Arctic countries. The study area has the potential to be a model for decarbonizing power generation systems in sensitive northern climates. With that would come significant social progress giving locals the opportunity to re-establishing the self-sustaining values passed on for centuries by the Inuit.

Chapter 6: Conclusion, Limitations, and Future Research

The future of energy usage in Nunavut is at a crossroads. The diesel generators currently being used will soon be decommissioned and the topic of renewable energy and self-sufficiency is making its way into territorial legislature. Shifting to a sustainable energy plan is integral for minimizing the challenges that overhauling the current power system will bring. This research project explores the potential, the costs, and the social need for developing renewable energy in Nunavut and the town of Rankin Inlet. By understanding Nunavut and Inuit history, the availability of natural resources, and the political incentive behind developing and reconciling northern communities, we can capture a holistic view of the current energy conundrum.

Through analyzing the technical feasibility of renewable energy technologies such as solar and wind a number of key findings were made evident. A 3.2 M solar PV plant could reduce diesel electricity usage by approximately 21% and eliminate 2,855 tonnes CO_{2eq} of GHG emissions. A solar plant could also reduce the current electricity cost from 0.49 $/kWh to 0.17 $/kWh. Wind farming proved to be more successful in the simulations, reducing diesel by 56% and eliminating 7,614 CO_{2eq} of GHG emissions. A 3.0 MW wind installation could also reduce the electricity cost from 0.49 $/kWh to 0.07 $/kWh. Minimizing energy expenditures and freeing-up funds for other valuable social programs such as health and housing is probably the most important benefit of a renewable energy development model for Rankin Inlet.

Understanding the social opinions of the current diesel generation system, as well as attitudes about renewable energy, gives perspective as to the best approach for the road ahead. Respondents to the survey expressed the greatest concern over environment and health issues surrounding diesel electricity production, while feeling cost of development as being the major hurdle for solar or wind projects. Nunavummiut attitudes regarding the best renewable energy solution varied between solar and wind, but wind was preferred. The next step for creating a renewable energy portfolio for Rankin Inlet is to collect precise resource data through wind and solar monitoring programs at potential project site locations.

The results of this study conclude that when the currently utilized, but outdated, diesel generation station is to be replaced, a hybrid system should be considered when proposing new electricity infrastructure. A hybrid system consisting of updated, more fuel-efficient diesel generation supplemented with a wind turbine and battery storage system is a viable, cost-effective, and environmentally conscious alternative. Solar panels could also be incorporated into the energy mix, but should be considered secondarily to wind. Given the excessive costs, health concerns, and environment impacts of maintaining a system entirely based on diesel, it is in the best interests of the Government of Nunavut and the Nunavummiut to start harnessing their abundant natural energy on a larger scale.

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Appendix A: Survey Questions

Below are the questions asked during the survey process for this study. The survey was conducted blindly through cold-calling, thus, respondents were contacted randomly. No preference was given to any of the respondents. Answers were summarized for the convenience of data plotting.

1) How long have you lived in Rankin Inlet?
2) What is your view on renewable energy technologies, such as solar panels and wind turbines?
3) Do you think renewable energy technologies would be a good fit for Rankin Inlet?
4) What kind of action would you like to see from your energy provider regarding renewable energy development?
5) How would you describe the energy source that currently powers your community?
6) Do you have any reservations or issues with the current diesel power plants?
7) What impacts do you see as a result of diesel generation?
8) What do you think are the barriers for renewable energy development in Rankin Inlet?
9) What are your impressions about renewable energy?
10) Do you think wind energy could work in Rankin Inlet?
11) Do you think solar power could work in Rankin Inlet?
12) Do you have any reservations about solar and/or wind power?
13) What impacts do you see as a result of renewable energy development?
14) Do you think your government will support new renewable energy developments for Rankin Inlet?
15) Do you think renewable energy could improve the quality of living in Rankin Inlet?

Appendix B: Financial Analysis

Table B- 1: Project costs considered to calculate IRR.

Cost of solar PV array	10,000,000
Cost of battery	2,100,000
Total cost of PV+battery install	12,100,000
Interest Rate %	n/a
Annual O&M	385,000
Inverter cost a 10 years	420,000
Electricity produced kWhr/y	3,407,000
Annual power sales (kWhr/y x $0.49)	1,669,430
Cash flow = power sales - O&M	1,284,430
Cash Flow @ 10 years - inverter	864,430
IRR Calculation	
cost of initial investment	-12,100,000
electricity revenue year 1	1,284,430
electricity revenue year 2	1,284,430
electricity revenue year 3	1,284,430
electricity revenue year 4	1,284,430
electricity revenue year 5	1,284,430
electricity revenue year 6	1,284,430
electricity revenue year 7	1,284,430
electricity revenue year 8	1,284,430
electricity revenue year 9	1,284,430
electricity revenue year 10	864,430
electricity revenue year 11	1,284,430
electricity revenue year 12	1,284,430
electricity revenue year 13	1,284,430
electricity revenue year 14	1,284,430
electricity revenue year 15	1,284,430
electricity revenue year 16	1,284,430
electricity revenue year 17	1,284,430
electricity revenue year 18	1,284,430
electricity revenue year 19	1,284,430
electricity revenue year 20	1,284,430
IRR	8.35%

(Byrne, 2018)

Table B- 2: PV + battery project payback period

Payback Period: **9.625 years**

Discounted Payback Period: **9.625 years**

Cash Flow Return Rate: **8.35% per year**

	Cash Flow	Net Cash Flow	Discounted Cash Flow	Net Discounted Cash Flow
Year 0	$-12,100,000.00	$-12,100,000.00	$-12,100,000.00	$-12,100,000.00
Year 1	$1,284,430.00	$-10,815,570.00	$1,284,430.00	$-10,815,570.00
Year 2	$1,284,430.00	$-9,531,140.00	$1,284,430.00	$-9,531,140.00
Year 3	$1,284,430.00	$-8,246,710.00	$1,284,430.00	$-8,246,710.00
Year 4	$1,284,430.00	$-6,962,280.00	$1,284,430.00	$-6,962,280.00
Year 5	$1,284,430.00	$-5,677,850.00	$1,284,430.00	$-5,677,850.00
Year 6	$1,284,430.00	$-4,393,420.00	$1,284,430.00	$-4,393,420.00
Year 7	$1,284,430.00	$-3,108,990.00	$1,284,430.00	$-3,108,990.00
Year 8	$1,284,430.00	$-1,824,560.00	$1,284,430.00	$-1,824,560.00
Year 9	$1,284,430.00	$-540,130.00	$1,284,430.00	$-540,130.00
Year 10	$864,430.00	$324,300.00	$864,430.00	$324,300.00
Year 11	$1,284,430.00	$1,608,730.00	$1,284,430.00	$1,608,730.00
Year 12	$1,284,430.00	$2,893,160.00	$1,284,430.00	$2,893,160.00
Year 13	$1,284,430.00	$4,177,590.00	$1,284,430.00	$4,177,590.00
Year 14	$1,284,430.00	$5,462,020.00	$1,284,430.00	$5,462,020.00
Year 15	$1,284,430.00	$6,746,450.00	$1,284,430.00	$6,746,450.00
Year 16	$1,284,430.00	$8,030,880.00	$1,284,430.00	$8,030,880.00
Year 17	$1,284,430.00	$9,315,310.00	$1,284,430.00	$9,315,310.00
Year 18	$1,284,430.00	$10,599,740.00	$1,284,430.00	$10,599,740.00
Year 19	$1,284,430.00	$11,884,170.00	$1,284,430.00	$11,884,170.00
Year 20	$1,284,430.00	$13,168,600.00	$1,284,430.00	$13,168,600.00

(Adapted from Calculator.net, 2018)

Table B- 3: Wind + battery project costs considered to calculate IRR

Cost of solar PV array	10,000,000
Cost of battery	3,500,000
Total cost of PV+battery install	13,500,000
Interest Rate %	n/a
Annual O&M	750,000
Gearbox cost a 10 years	500,000
Electricity produced kWhr/y	9,733,000
Annual power sales (kWhr/y x $0.49)	4,769,170
Cash flow = power sales - O&M	4,019,170
Cash Flow @ 10 years - gearbox	3,519,170
IRR Calculation	
cost of initial investment	-13,500,000
electricity revenue year 1	4,019,170
electricity revenue year 2	4,019,170
electricity revenue year 3	4,019,170
electricity revenue year 4	4,019,170
electricity revenue year 5	4,019,170
electricity revenue year 6	4,019,170
electricity revenue year 7	4,019,170
electricity revenue year 8	4,019,170
electricity revenue year 9	4,019,170
electricity revenue year 10	3,519,170
electricity revenue year 11	4,019,170
electricity revenue year 12	4,019,170
electricity revenue year 13	4,019,170
electricity revenue year 14	4,019,170
electricity revenue year 15	4,019,170
electricity revenue year 16	4,019,170
electricity revenue year 17	4,019,170
electricity revenue year 18	4,019,170
electricity revenue year 19	4,019,170
electricity revenue year 20	4,019,170
IRR	29.52%

(Byrne, 2018)

Table B- 4: Wind + battery project payback period

Payback Period: **3.359 years**

Discounted Payback Period: **3.359 years**

Cash Flow Return Rate: **29.52% per year**

	Cash Flow	Net Cash Flow	Discounted Cash Flow	Net Discounted Cash Flow
Year 0	$-13,500,000.00	$-13,500,000.00	$-13,500,000.00	$-13,500,000.00
Year 1	$4,019,170.00	$-9,480,830.00	$4,019,170.00	$-9,480,830.00
Year 2	$4,019,170.00	$-5,461,660.00	$4,019,170.00	$-5,461,660.00
Year 3	$4,019,170.00	$-1,442,490.00	$4,019,170.00	$-1,442,490.00
Year 4	$4,019,170.00	$2,576,680.00	$4,019,170.00	$2,576,680.00
Year 5	$4,019,170.00	$6,595,850.00	$4,019,170.00	$6,595,850.00
Year 6	$4,019,170.00	$10,615,020.00	$4,019,170.00	$10,615,020.00
Year 7	$4,019,170.00	$14,634,190.00	$4,019,170.00	$14,634,190.00
Year 8	$4,019,170.00	$18,653,360.00	$4,019,170.00	$18,653,360.00
Year 9	$4,019,170.00	$22,672,530.00	$4,019,170.00	$22,672,530.00
Year 10	$3,519,170.00	$26,191,700.00	$3,519,170.00	$26,191,700.00
Year 11	$4,019,170.00	$30,210,870.00	$4,019,170.00	$30,210,870.00
Year 12	$4,019,170.00	$34,230,040.00	$4,019,170.00	$34,230,040.00
Year 13	$4,019,170.00	$38,249,210.00	$4,019,170.00	$38,249,210.00
Year 14	$4,019,170.00	$42,268,380.00	$4,019,170.00	$42,268,380.00
Year 15	$4,019,170.00	$46,287,550.00	$4,019,170.00	$46,287,550.00
Year 16	$4,019,170.00	$50,306,720.00	$4,019,170.00	$50,306,720.00
Year 17	$4,019,170.00	$54,325,890.00	$4,019,170.00	$54,325,890.00
Year 18	$4,019,170.00	$58,345,060.00	$4,019,170.00	$58,345,060.00
Year 19	$4,019,170.00	$62,364,230.00	$4,019,170.00	$62,364,230.00
Year 20	$4,019,170.00	$66,383,400.00	$4,019,170.00	$66,383,400.00

(Adapted from Calculator.net, 2018)