Design and Analysis of a Sustainable Energy System for a Military Base in the Canadian Arctic

by

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A thesis submitted to the
School of Graduate and Postdoctoral Studies in partial
fulfillment of the requirements for the degree of

Master of Applied Science in Mechanical Engineering

Department of Mechanical and Manufacturing Engineering/ Faculty of Engineering and Applied Science

University of Ontario Institute of Technology (Ontario Tech University)

Oshawa, Ontario, Canada

August 2023

Thesis Examination Information

Submitted by: **Mark Ironside**

Master of Applied Science in Mechanical Engineering

Thesis title: **Design and Analysis of a Sustainable Energy System for a Military Base in the Canadian Arctic**

An oral defense of this thesis took place on July 24, 2023 in front of the following examining committee:

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The above committee determined that the thesis is acceptable in form and content and that a satisfactory knowledge of the field covered by the thesis was demonstrated by the candidate during an oral examination. A signed copy of the Certificate of Approval is available from the School of Graduate and Postdoctoral Studies.

Abstract

The purpose of this thesis was to propose and thermodynamically analyze a sustainable energy system for a military base in the Canadian Arctic for heating, electricity, farming, fresh water, hot water and waste management. This study is relevant because of the opening up of the Arctic passages and the consequent increase of military presence there. Therefore, an integrated wind powered energy generation system has been proposed and thermodynamically analyzed. The system was designed with a capacity of 51 MW and hydrogen storage of 229 tons. The results show promise with energy and exergetic efficiencies of 64% and 41%, respectively. Furthermore, the proposed system has lower lifecycle costs and emissions than that of its diesel counterparts, which are generally employed in northern Canada.

Keywords: Wind turbine; Arctic; heat pump; hydrogen; sustainable energy

Author's Declaration

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I hereby certify that I am the sole author of this thesis and that no part of this thesis has been published or submitted for publication. I have used standard referencing practices to acknowledge ideas, research techniques, or other materials that belong to others. Furthermore, I hereby certify that I am the sole source of the creative works and/or inventive knowledge described in this thesis.

Acknowledgments

This thesis would not have been possible without the support and guidance provided by my supervisor, Dr. Martin Agelin-Chaab. Throughout my master's program, he has provided me with motivation and counsel that I will continue to use throughout my life. His time commitment and dedication through our many meetings and reviews were invaluable – thank-you.

To my parents – Mum and Dad, thank-you for the love and support you have provided me throughout my life. Without your help and determination I would not be where or who I am today.

Finally, thank-you to my wife, Jillien, and children Ella, Lauren, Daniel and Owen for your love, patience and confidence in me and for all the sacrifices you have had to make as I pursue my Master's Degree – I could not have done it without you.

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Abbreviations

A-CAES	Adiabatic compressed air energy storage
ASHP	Air source heat pump
BiPV	Bifacial PV
COP	Coefficient of performance
CSP	Concentrated solar power
DND	Department of National Defence
DNI	Direct normal irradiation
EES	Engineering Equation Solver
FESS	Flywheel energy storage system
GHG	Greenhouse Gas
GPP	Geothermal power plants
GSAHP	Ground source absorption heat pumps
GSEHP	Ground source electrical heat pumps
GSHP	Ground source heat pumps
HP	High pressure
HP	Heat pump
HT	Hydro turbine

HTF	Heat transfer fluid
HTW	High temperature well
LCOE	Levalized cost of electricity
LHS	Latent heat storage
LP	Low pressure
LTW	Low temperature well
NREL	National Renewable Energy Laboratory
ORC	Organic Rankine cycle
OTEC	Ocean thermal energy conversion
PCM	Phase change material
PEMFC	Proton exchange membrane fuel cell
PHES	Pumped hydro energy storage
PV	Photovoltaic
PVT	Photovoltaic thermal
SA	Solar assisted
SMES	Superconducting magnetic energy storage
SOFC	Solid Oxide Fuel Cell
TES	Thermal energy storage
TOS	Thermal Oxidation System
WPD	Wind power density

Units

BTU	British Thermal Units
℃	Degrees Centigrade
cm	centimeter
ºF	Degrees Fahrenheit
gCO_2/kWh	grams CO_2/kWh
GW	Gigawatt
kg	kilogram
kg/s	mass flow rate
kJ/kg	Specific Enthalpy
kJ/kg-K	Specific Entropy
Km	Kilometer
kPa	kilopascal
kWh	kilowatt hour
kWh/m^2	Direct normal irradiation
L	Litres
m	meter
MJ/m^2	Megajoule/square meter
m/s	meters/second
m^3/s	cubic meters/second

MW	Megawatt
ºN	Degrees north
PJ	Petajoule
PWh	Petawatt hour
t CO_2	Tons carbon dioxide
TW	Terawatt
ºW	Degrees west
W/m^2	Watts/square meter

Symbols

$\dot{E}x$	Exergy destruction rate
ex	Specific exergy
h	Specific enthalpy
$\dot{m}$	Mass flow rate
η	efficiency
$\dot{Q}$	Heat rate
$\dot{S}$	Entropy rate
s	Specific entropy
$\dot{W}$	Power

Chapter 1: Introduction

1.1 Background

The need to prioritize and accelerate the development of sustainable energy on a global scale largely began in the 1970s [1] with the publication of Limits to Growth [2]. This publication was the first of its kind [1], predicting a global environmental and economic collapse [2]. Over 30 years later, a further update was provided in “Limits to Growth: The 30-Year Update” [3]. Regardless of the scenario presented, each resulted in a full and abrupt societal collapse [3].

The report of the World Commission on Environment and Development: Our Common Future [4] in 1987 defined sustainable development as “…development that meets the needs of the present without compromising the ability of future generations to meet their own needs”. In contrast to the sustainable development definition, the industrialization of economies across the globe has accelerated greenhouse gas (GHG) emissions, causing detrimental impacts on the environment and humanity, including premature death [5]. The main contributors to GHGs, predominantly carbon dioxide, are electricity, heat and transportation derived from fossil fuels [6]. In 2013, the Intergovernmental Panel on Climate Change found that since 1951 the increased global industrialization and accumulated carbon dioxide in the atmosphere are the primary drivers of climate change [7].

Economically speaking, the impact of climate change in Canada could cost up to $43 billion per year in 2050 [8]. The impacts driving this cost range from increasing healthcare costs to agricultural decline. In a 2015 projection of fossil fuel production, Canada is projected to be a major contributor to oil and gas production, with its peak between 2075-2091 [9]. Further, Canada’s yearly GHG emissions have been projected to increase year over year until at least 2050, with the mining, oil and gas sectors making up the majority of emissions [10].

In response to the potential risks climate change threatens and in response to international commitments, particularly The Paris Agreement [11], the government of Canada, in 2021, introduced the Canadian Net-Zero Emissions Accountability Act [12]. This act has introduced a net-zero GHG emissions target by the year 2050. Previous to the introduction of this act, Canada has largely failed in relation to climate policy and goals [13].

In Canada, GHG emissions are predominantly represented by six main sources [13]:

1. Oil and Gas extraction: 26%
2. Transportation: 24%
3. Electricity: ~10%
4. Buildings: ~10%
5. Industry: ~10%
6. Agriculture: ~10%

In accordance with the Paris Agreement, developed countries, such as Canada, should be an example to developing nations, reducing emissions across all sectors – including the defence sector [11]. From 2020 – 2021, the emissions from the Canadian defence sector accounted for approximately 50% of the total Government of Canada emissions [14]. The Greening Government Strategy sets out the strategy for the Government of Canada’s alignment with the Canadian Net-Zero Emissions Accountability Act, dictating the implementation of net-zero in property and fleet operations for the defence sector [15]. Further, in response, the Department of National Defence (DND) has released the Defence Energy and Environment Strategy outlining its strategy to reduce

GHG emissions. Of particular note is the indication that improvements are needed in environmental sustainability while maintaining operational requirements in the Arctic region [16].

The three territories of Canada, the Yukon, Northwest Territories and Nunavut, all north of the 60th parallel, make up some of Canada's coldest and most harsh environments. Total energy consumption in these territories in 2019 amounted to 32.5 PJ of which 25.7 PJ was derived from fossil fuels contributing to Canada's overall GHG emissions [17]. In addition to the negative environmental impacts, fossil fuels generate an excessive financial burden in the northern territories as a result of lengthy transportation, poor infrastructure and maintenance costs [18]. Although GHG emissions in the Canadian Arctic are not significant relative to many parts of the country, the aforementioned negative impacts of fossil fuel use in the Arctic make it important to explore and invest in sustainable energy development for the north.

1.2 Motivation

Throughout the Cold War, there was a drive to explore and understand the Canadian Arctic in order to enhance national security and aid in military planning and strategy [19]. Thirty years later, with a changing climate, the Arctic is again coming into focus as the exposure to new transportation routes and resources drives the potential for military conflict [20]. As a result of this increased threat, the Canadian military has been increasing its military presence in the Arctic in order to defend Canada's sovereignty [21]. The Canada First Defence Strategy included a number of Arctic defence strategies to be employed, including additional domestic operations in the Arctic, new Arctic ships, maritime patrol aircraft, radars and satellites [22]. Lessons learned from several Arctic military exercises have also uncovered the need to develop Arctic hubs in order to sustain Canadian forces deployed without relying on the northern community resources [21]. This sentiment is further echoed in the Canada Defence Policy Report presentation of initiative 106: "*Enhance the mobility, reach and footprint of the Canadian Armed Forces in Canada's North to support operations, exercises, and the Canadian Armed Forces' ability to project force into the region*" [23]. It is currently understood that there is no immediate need for a permanently manned large-scale military base in the Arctic due to the presence of the Canadian Rangers and the mobilization of the Arctic Response Groups; however, as additional threats emerge, a larger military presence may be required [20]. As a result of the de-scoping of the original Nanisivik Naval Facility project, a longer-term gap has emerged in supporting the Canadian Armed Forces [24]. With the Nanisivik project came resentment from northern communities as it did not provide any clear economic or societal benefits for the communities [25]. Future northern military installations should not only seek to provide benefits for northern communities but, in line with Canada's emissions targets, be developed sustainably.

1.3 Objectives

The objective of this thesis is to develop sustainable energy solutions for a military base in the Canadian Arctic. The proposed systems will be designed to support heating, electricity, farming, hot water, fresh water and a number of military requirements for an Arctic base. As previously discussed, Canada is expanding its military reach in the northern territories due to increased threats and voyages in the north. In order to support this expansion, the proposed military base will seek to meet similar requirements set out by the Department of National Defence for the Nanisivik Naval Facility project in 2007 while utilizing as much existing infrastructure as possible. In addition to these requirements, the military base will have the ability to support an additional 1000 personnel in order to support northern operations such as Operation Nanook [26].

The specific objectives include:

i. To propose and analyze a sustainable energy solution for a military base in the Canadian Arctic for heating, electricity, farming, hot water, waste management and previously specified military applications.

ii. To conduct a comprehensive thermodynamic analysis of the proposed system.

iii. To perform parametric analyses of the proposed energy systems.

1.4 Thesis Structure

The outline of this thesis is as follows:

Chapter 1 provides the background, motivation and objectives of this work.

Chapter 2 presents a review of existing literature relating to potential renewable energy sources in the Arctic and applicable energy systems.

Chapter 3 describes the methodology underpinning the development of the energy system presented.

Chapter 4 discusses the results of the modelling and simulation and compares the performances of the energy system presented.

Chapter 5 provides a summary of this work and highlights recommendations and potential future work.

Chapter 2: Literature Review

As a consequence of the increased global attention toward the negative impacts of the use of fossil fuels, more renewable energy sources have been sought and increasingly studied and improved. Six renewable energy sources account for the majority of research in the pursuit of a net zero planet, including geothermal, wind, hydro, marine, solar and biomass. Additionally, as a result of energy demand cycles and the varied energy supply of some renewable sources, energy storage studies and proposed solutions have also dominated the renewable energy literature. This chapter will review the six renewable energy sources mentioned here, with an analysis of existing literature on the potential performance of each source in the Canadian Arctic, for both stand-alone and hybrid systems.

2.1 Geothermal

2.1.1 Introduction

Geothermal has significant potential in the development of sustainable energy. In comparison with the estimated potential fossil fuel energy, the geothermal potential within 3km of the earth's crust is over 1000 times greater [27]. However, geothermal is still largely cost prohibitive due to the high financial impacts of drilling and exploration [28]. The categorization of geothermal is based on the available temperatures – low (<100°C), middle (100-180°C) and high (>180°C) and can be further categorized into applications, technology & source:

Table 2.1: Geothermal classification, resources and technologies [28]

Geothermal Categories	Temperature Range	Geothermal Resource Type	Technology use Potential
Low-Temperature	<100°C	Hot-water dominated (20-350°C) Sedimentary basin (20-150°C) Radiogenic (30-350°C) Geopressured (90-200°C) Hot dry rock (90-650°C)	Heat exchangers Heat pumps Power Generation (ex. Binary cycle)
Middle-Temperature	100-180°C	Hot-water dominated (20-350°C) Sedimentary basin (20-150°C) Radiogenic (30-350°C) Geopressured (90-200°C) Hot dry rock (90-650°C)	Heat exchangers Heat pumps Power Generation (ex. Binary cycle)
High-Temperature	>180°C	Hot-water dominated (20-350°C) Radiogenic (30-350°C) Geopressured (90-200°C) Hot dry rock (90-650°C) Vapor-Dominated (~240°C) Magma (>600°C)	Heat exchangers Heat pumps Power Generation (ex. Flash/Binary combined cycle)

As indicated in Table 2.1, geothermal has been used both directly for heating/cooling and for power generation. However, the geothermal resource and temperature range dictate the technology used for both direct application and power generation. The following will explore the geothermal potential in the Canadian Arctic and review both novel direct geothermal applications and geothermal power generation systems.

2.1.2 Geothermal potential in the Canadian Arctic

Canada has significant geothermal potential energy across the country, including northern Canada [29]. However, to date, geothermal energy in Canada has only been used for direct heat applications [30]. Figure 2.1 illustrates the distribution of potential geothermal energy sources across Canada.

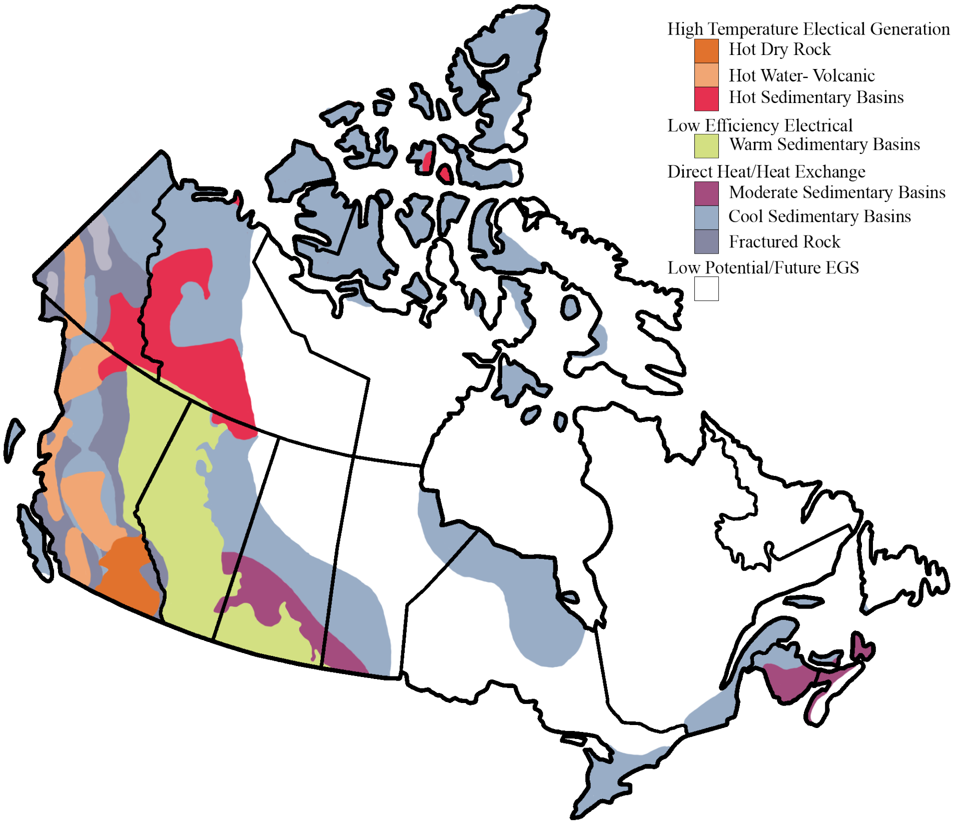

Figure 2.1: Geothermal resource in Canada [31]

While it is clear, based on Figure 2.1, that Northern Canada has an abundance of geothermal potential, drilling depth to achieve this potential also has to be factored in. Current technology limits drilling to approximately 6 km, and therefore geothermal potential is limited up to this depth at this time [32]. Within the constraints of drilling technology, Figure 2.2 provides an image of northern Canada and potential geothermal temperatures.

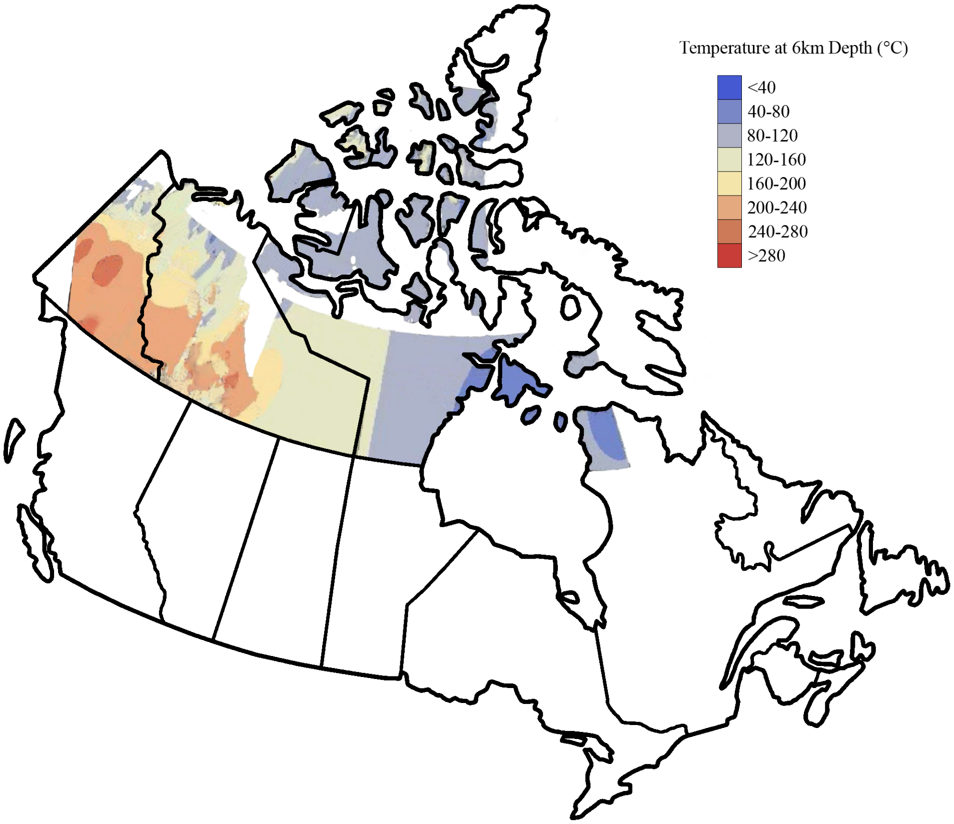

Figure 2.2: Temperature at 6 km depth [32]

Based on the geothermal potential distribution in Northern Canada and the current dependency on diesel for heating and energy in many remote communities, geothermal energy development in the North has the potential to reduce both energy costs and GHG emissions [31].

Economically, the authors of a recent article examining the feasibility of geothermal energy systems for Artic communities found it to be a viable solution in reducing diesel dependency [33]. However, it was also noted that the infrastructure costs could be two to five times greater than average in remote areas. Installation costs can also be significantly higher due to the presence of permafrost and the requirement for specialized equipment [34].

The development of any geothermal resource in the Artic also needs to take into account societal constraints, including the impact on the land and its use. Over half of Canada's Arctic population is Indigenous, emphasizing the need for consultation with local communities to prevent infringement on sustenance rights or impact on significant archeological sites [35]. In addition to clean, reliable energy, food instability is also a concern in Canada’s Arctic region. While geothermal energy has the potential to produce both sustained food production in greenhouses and reliable energy the aforementioned limitations in the Arctic currently make geothermal an unrealistic energy source in the Canadian Arctic region [36]. Therefore, current geothermal energy systems have been omitted in this review.

2.2 Wind Power

2.2.1 Introduction

Wind energy has been harnessed as early as 5000 BC and continues today as one of the fastest accelerating energy sources in the world [37]. The potential to exploit wind energy for power production depends on both wind variability and wind speed [38]. Wind energy potential can be quantitatively classified as per Table 2.2 Wind Power Classification [38] and used when comparing potential sites.

Table 2.2: Wind power classification [38]

Wind Power Class	Resource Potential	Wind Power Density (W/m^2)	Wind Speed (m/s)
1	Poor	0 – 200	0.0 – 5.9
2	Marginal	200 – 300	5.9 – 6.7
3	Fair	300 – 400	6.7 – 7.4
4	Good	400 – 500	7.4 – 7.9
5	Excellent	500 – 600	7.9 – 8.4
6	Outstanding	600 – 800	8.4 – 9.3
7	Superb	> 800	>9.3

Based on an improved estimation of wind resources around the world, the National Renewable Energy Laboratory (NREL) has estimated the total potential to be 560 PWh and 315 PWh for terrestrial wind and offshore, respectively [39]. Meanwhile, a 2020 global wind power generation analysis found the current power generation to be less than 2% of this potential [40]. It can therefore be concluded that there is significant growth potential in wind power. Like many countries, Canada has increased its investment in wind energy, hitting a 14 GW installed capacity in 2021 [41]. Though this wind energy capacity is one of the highest in the world, it only makes up approximately 5% of the total energy generated in Canada [42]. The following will explore the wind potential in the Canadian Arctic and review novel wind energy production and relevant recent research in this field.

2.2.2 Wind power potential in the Canadian Arctic

Canada’s total installed wind energy capacity is marginal compared to overall capacity. Figure 2.8 illustrates the breakdown of wind energy capacity compared to overall energy capacity as of 2020 in Canada. While the total installed wind energy capacity across Canada is approximately 10% of the overall capacity, the wind energy capacity of Canada’s Territories is less than 2% of their overall capacity. In a six year study of Canadian wind farms, it was found that power production losses were consistently higher in winter months than in summer, demonstrating the need for additional research and development in wind energy production in cold climates [43]. This reduction in power production in cold climates could therefore point to the lack of significant wind investment in northern communities. Contributing to the reduced performance, ice accretion on turbine blades, particularly relevant in Canada’s Arctic region, has also resulted in surface erosion and blade failures [44].

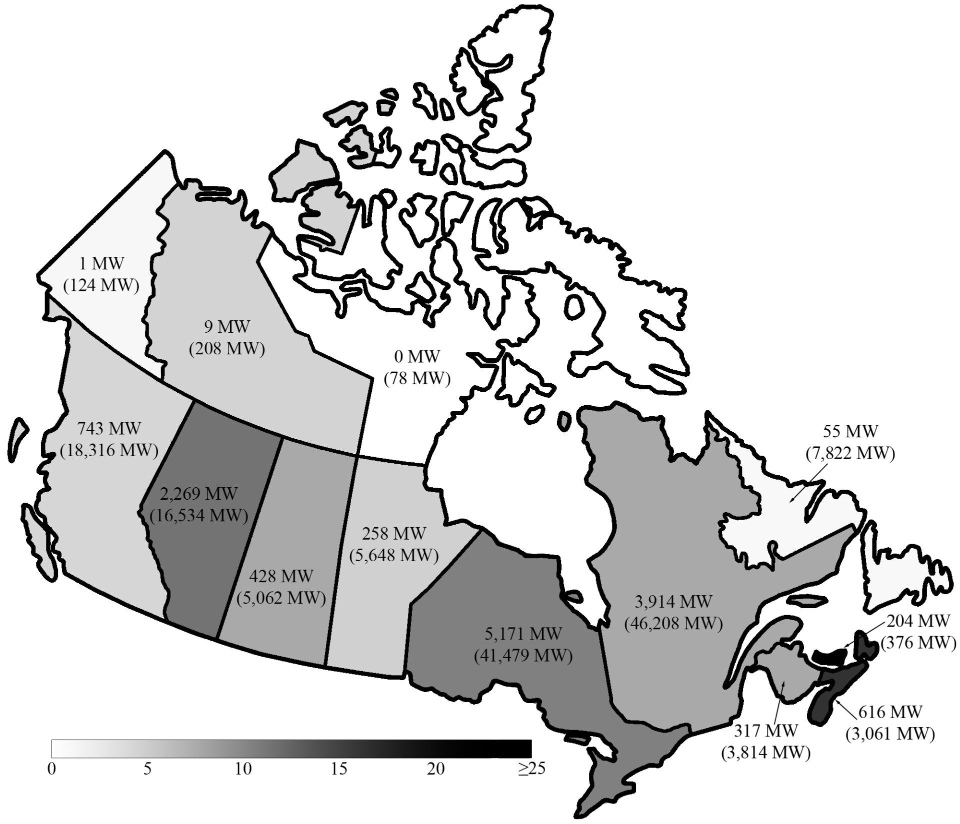

Figure 2.3: Wind capacity vs total capacity [41]

In addition to reduced turbine performance in cold climates and ice accretion challenges, the majority of offshore wind power potential in the Canadian Arctic is the lowest, with wind power density (WPD) between 140-300 W/m^2 [45]. Nevertheless, the onshore WPD, as seen in Figure 2.9, in the Canadian Arctic has the potential of being harnessed to support northern communities not connected to a grid and are currently reliant on diesel fuels [46].

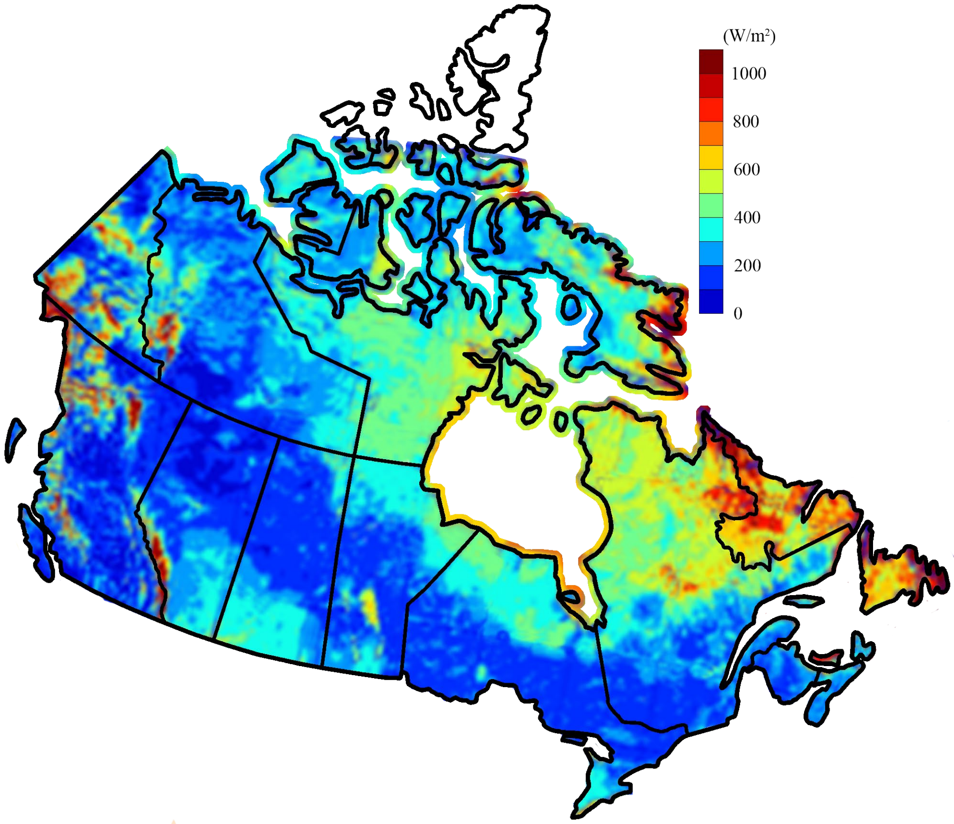

Figure 2.4: Wind power density Canada simulation [47]

Similar to geothermal in the Canadian Arctic, while more costly due to the remote communities in the north, on-shore wind power is seen to be an economically viable option for reducing diesel usage in northern communities [48]. Off-shore wind power in the Canadian Arctic, however, requires further research and investigation due to the compounded challenges of ice formations and a potential increase in ice accretion [49].

Wind power is also not without its societal and environmental impacts, which should be considered. Societally, wind turbine installations impact land and open water use, create noise pollution and provide potential negative visual impacts [50]. Environmentally, impacts include increased avian mortality, habitat loss, forced changes in avian migration, noise impacting marine/land life and vegetation impacts [50]. While technologies are being improved upon to minimize environmental concerns, it remains imperative to engage with local communities with proposed turbine installations.

2.2.3 Wind energy systems

Wind power has the potential to provide energy directly via wind turbines or indirectly through integration into an energy system. As noted, onshore wind resource in the Canadian Arctic has potential due to sufficient wind density; however, cost continues to be prohibitive as initial costs are high and electricity produced is typically intermittent [37]. This sub-section focuses on current research in wind energy systems and potential solutions to one problem wind energy currently faces – variability.

Several studies have sought to reduce the intermittency of wind power through novel system designs. In one such study, a wind powered hydraulic pump was used to pump water from a well to a reservoir for pumped-hydro energy storage (PHES). The water head would in turn, power a generator producing constant and reliable electricity regardless of intermittent wind power [51]. While utilizing PHES is not a unique idea, the presented system's novelty was through the use of the wind turbine to direct power the hydraulic pump, as seen in Figure 2.10. The system parameters for this design were based on requirements for rural electrification in remote locations. The authors found that for continuous operation, the wind speed required is above 4.6 m/s and with no wind, the system could produce power for nearly four hours. Overall, the system analysis proved to be effective at maintaining the required power based on the average wind speed data provided for the chosen location.

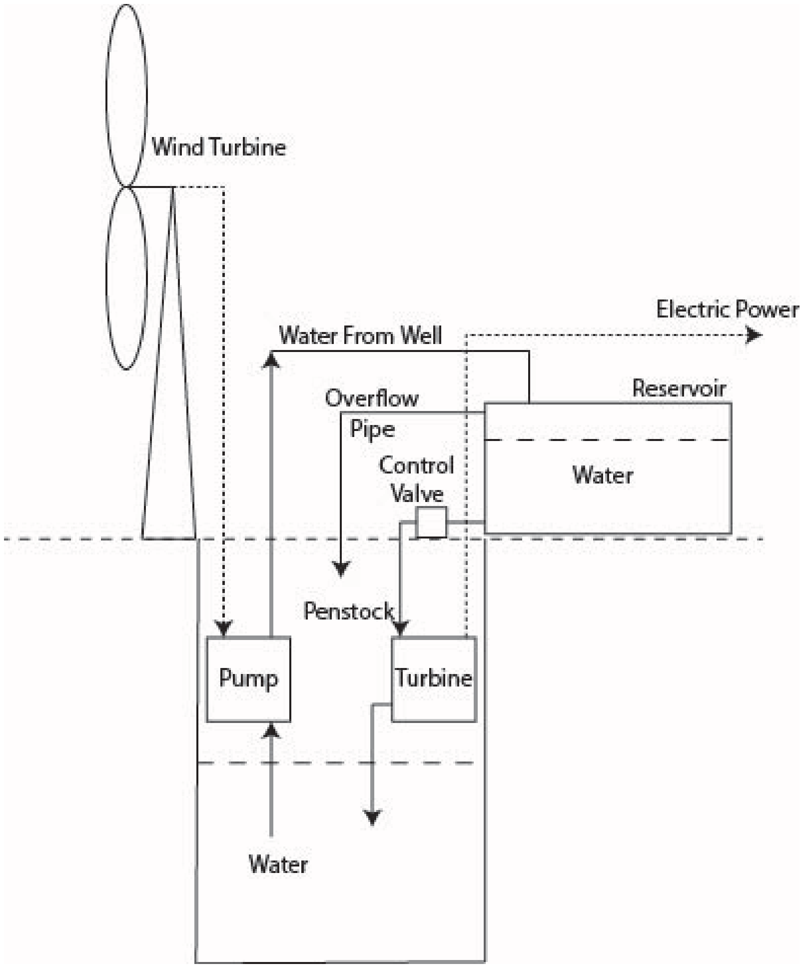

Figure 2.5: Wind powered PHES system [51]

In another wind powered system, a hybrid energy storage solution was presented using both adiabatic compressed air energy storage (A-CAES) and a flywheel energy storage system (FESS) [52]. In this system, surplus energy created via a wind farm is divided into two storage systems: the A-CAES system and the FESS. The A-CAES stores compressed air and heat from the compression process, whereas the FESS stores kinetic energy via flywheel. When the system demands additional energy that the wind farm cannot supply, the A-CAES system releases energy from the stored compressed air, heats it using the stored thermal oil and runs a high pressure (HP) and low pressure (LP) turbine to generate electricity whereas the FESS releases its kinetic energy by driving the generator with the flywheel rotor. The authors note that the fluctuations experienced in wind energy systems underpin the criticality of hybrid systems such as the one presented. In this system, the FESS can achieve a rapid response while the A-CAES system comes online.

Economically, wind powered hydrogen storage solutions have also been analyzed, as shown in Figure 2.11 [53]. Overall, the analysis done by the authors found that hydrogen-wind systems can be advantageous both economically and as a way to avoid grid limitations. The results found were similar to a case study for wind-hydrogen systems reviewed in five locations in Turkey with a yearly potential hydrogen production of 6288.59kgH_2 [54].

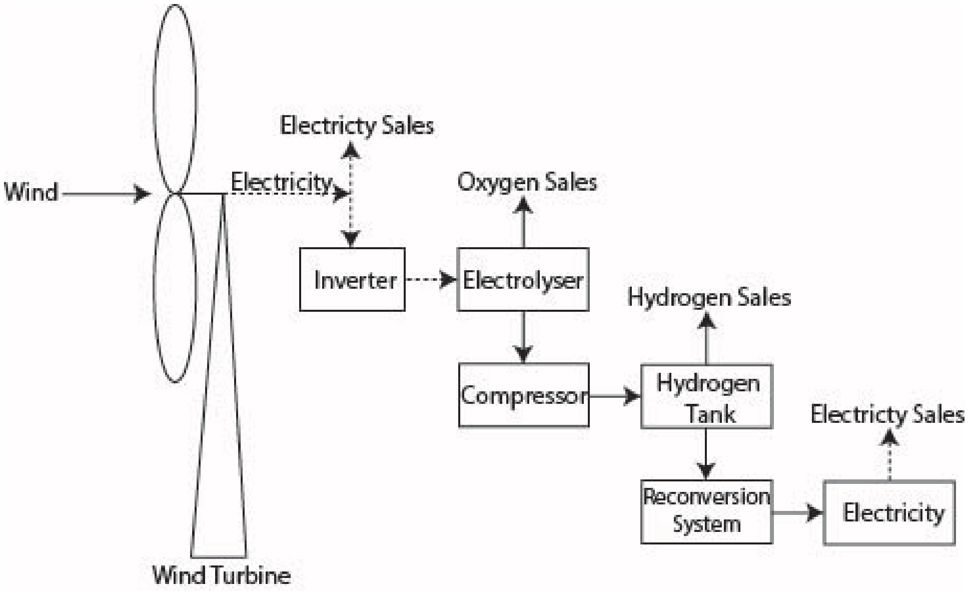

Figure 2.6: Wind powered hydrogen energy system [53]

Further studies have been reviewed for wind energy storage, including battery storage [55], superconducting magnetic energy storage (SMES) and super capacitor energy storage [56]. All these studies attempted to solve the problem of the erratic nature of wind power using energy storage solutions.

2.3 Hydropower and Marine Power

2.3.1 Introduction

As a percentage of total energy production, hydro only amounts to approximately 2.5%. However, ignoring biomass, hydro accounts for more than 50% of clean, renewable energy generation [57]. At the same time, marine power has minimal contributions to the amount of electricity generation worldwide. Hydropower has a number of advantages as a renewable energy source, including being well established, responsiveness to power demands, storage management and low emissions [58]. Marine power, meanwhile is not as established for harnessing the energy potential of waves, currents and tides. However, in a review of marine power potential, it was found that global potential marine resources could amount to as much as 3.7 TW [59]. Marine power can be categorized into five types, as seen in Table 2.3. Based on this table, it is clear a significant amount of attention has been given to the tidal range but the energy potential for other categories should not be discounted.

Table 2.3: Marine power categories and percentage of total marine power produced [60]

Marine Power Categories	Power Production Distribution
Wave Power	0.57%
Tidal Stream	1.34%
Tidal Range	98.04%
Salinity Gradient	0.01%
Ocean Thermal Energy Conversion (OTEC)	0.04%

The ways in which electricity can be generated from hydropower can be categorized into three power plant types: impoundment, diversion and pumped storage [61]. While categorized as renewable, it should be noted that both hydropower and marine power have environmental concerns which should be taken into account, including wildlife displacement, underwater noise and potential water contamination [62].

The following will explore both hydropower and marine power potential in the Canadian Arctic and also review novel hydropower and marine power energy production designs and relevant recent research in this field.

2.3.2 Hydropower and marine power in the Canadian Arctic

Canada is a major contributor of hydropower on the world stage, with over 9% of the world's hydroelectricity generation [63]. Furthermore, hydropower contributes to approximately 60% of power generated in Canada [64], with the potential to double its capacity, as seen in Figure 2.12

[65]. Similar to wind and geothermal, the Canadian Arctic has significant potential in the development of hydropower to reduce overall fossil fuel consumption.

Figure 2.7: Canadian hydropower capacity and potential [65]

With respect to marine energy however, several types are found to be particularly inefficient in the Canadian Arctic, as can be seen with wave potential in Figure 2.13 and with the OTEC boundary in Figure 2.14. However, continued research in this area includes alternative approaches to energy generation, including OTEC production through the heat differential between air and water in the Arctic, as proposed in the literature [66].

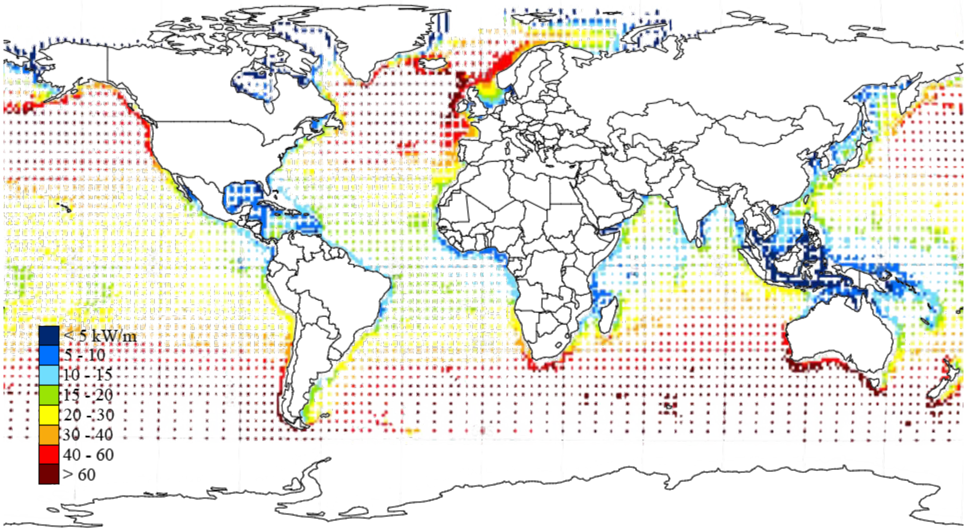

Figure 2.8: Annual global theoretical wave power [59]

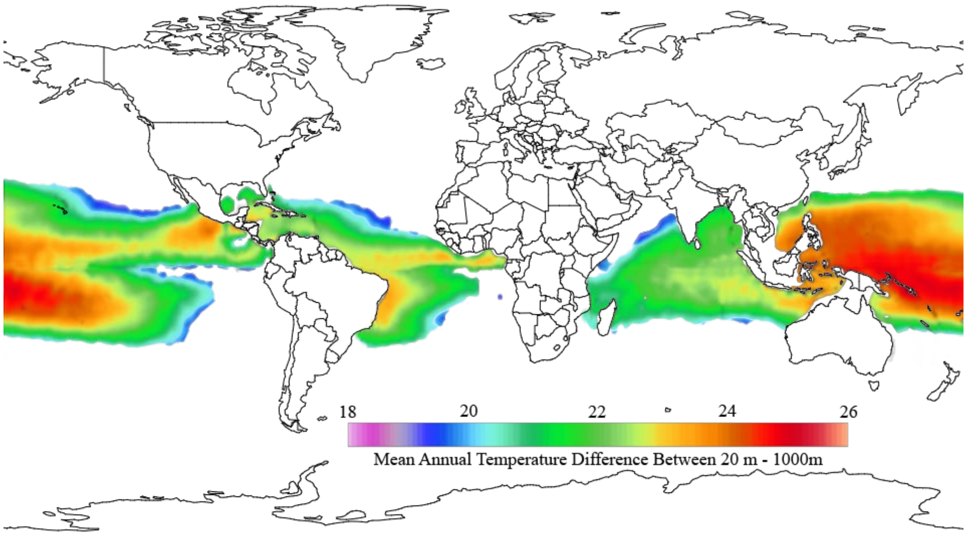

Figure 2.9: Average ocean temperature differences between 20 and 1000 m water depth [67]

Nevertheless, in a study reviewing tidal range and stream potential in the Canadian Arctic, the authors studied the Kokosoak hyper-tidal estuary to understand the effects of the Arctic winter on tidal power potential [68]. In this study, it was found that the ice and freezing temperatures should not be a barrier to future research and/or development of tidal resources in the Arctic as the tidal energy is not significantly impacted except during peak winter. Furthermore, the salinity gradient between these northern estuaries and the Arctic Ocean could be harnessed [69].

While hydropower is currently the highest used renewable source in the Arctic, the capital required for implementation is extensive. In general, hydropower plants are installed to support larger communities or ones supported by a grid, thus limiting many of Canada's northern communities [70]. A number of societal and environmental constraints also exist, including impacts on land and water use due to changes in river systems and impacts on marine mortality and fish migration.

2.3.3 Hydropower and marine power energy systems

The hydropower and marine power potential in Canada aforementioned is vast; however, these energy systems can carry both significant economic and environmental challenges [65]. Economically, hydropower and marine power have high upfront costs, which can pose barriers to adoption. Consequently, much of the literature on both hydropower and marine power energy systems seeks to improve efficiency through the adoption of hybrid systems, turbine design or theoretical optimization for power distribution as examples. The following will review current literature relating to hydropower and marine power and potential improvements being proposed.

In a combined PV-hydropower generation system, researchers [71] utilized a PV array as the primary energy for the system powering a pump in a lake to pump water to a storage tank at a higher altitude. The water from the tank flows into a head control tank which subsequently flows down to a hydro turbine (HT) – see Figure 2.15. The authors proposed this solution as a beneficial option for isolated communities where electricity is not an option, as significant water diversion or dam construction is not required. The system presented was analyzed to have a payback of less than eleven years and a LCOE of $0.0273 USD/kWh over fifty years.

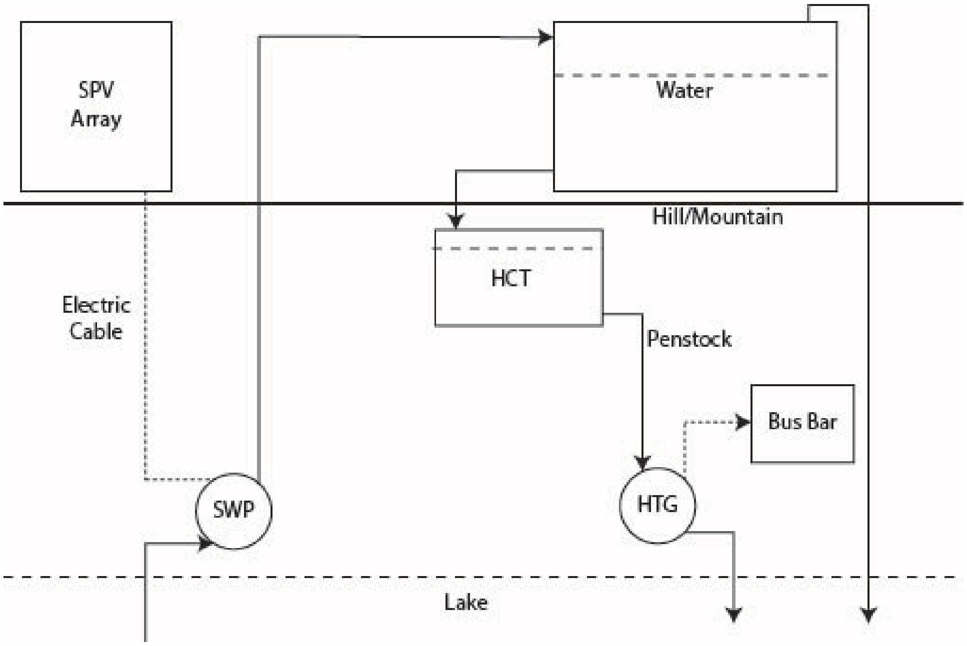

Figure 2.10: Hybrid solar-hydropower system [71]

On a larger scale, another study focused on reviewing the potential for increasing hydropower production through the utilization of tailwaters in existing hydropower stations through hydrokinetic turbines [72]. Five challenges were presented, including 1) current hydropower station feasibility, 2) environmental impact, 3) technology availability, 4) cost of energy, and 5) other factors such as reliability, social impacts and system performance. Although this approach has significant challenges, it was concluded that the potential to increase hydroelectric was promising and had the potential to decrease CO_2 emissions by up to 81 million metric tonnes [72]. Similarly, the potential of hydrokinetic turbines in three hydropower stations in Nigeria was assessed and found noteworthy improvements to overall production but with some challenges to implementation akin to those stated earlier [73].

In a design utilizing tidal range energy, a hybrid PV-tidal range system for the desalination of seawater in Figure 2.16 was analyzed [74] [75]. An optimal location and design variations were considered for the system to provide favourable results; benefits of the hybrid PV-tidal range system provided continued desalination during reduced PV energy generation with the capacity to incorporate energy storage solutions or feedback into the energy grid.

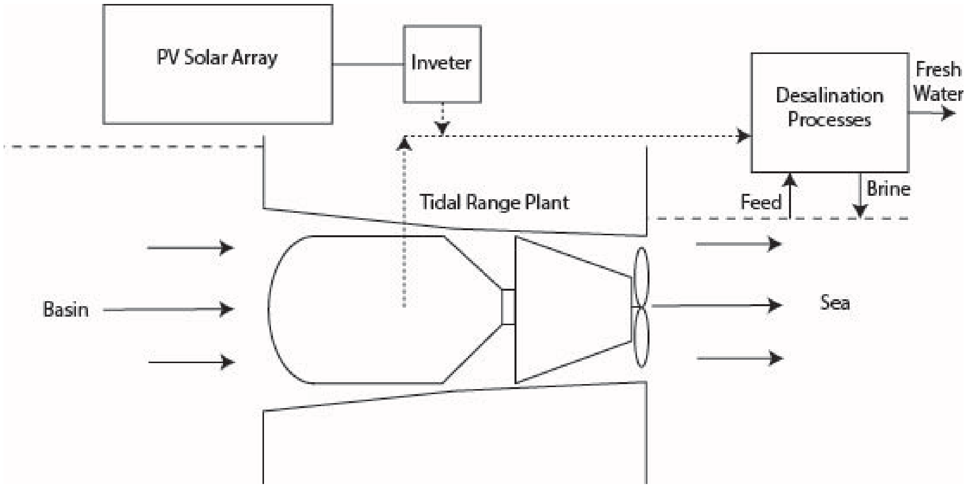

Figure 2.11: Hybrid PV-tidal range desalination system [75]

Significant research has also been dedicated to the turbines used in marine power systems, as shown in Table 2.4 [76]. A common theme among turbines presented is the environmental impact of the turbines, particularly the impact on marine life. While existing tidal range turbines have a significant impact on marine life mortality, the majority of potential tidal range turbines being explored offer a reduced impact on marine life.

Table 2.4: Tidal range overview [76]

Tidal Range Production Types	Tidal Range Barrage	Tidal Range Turbines	Potential Tidal Range Turbines
Ebb generation	Tidal Lagoons	Bulb Turbine	Modified Bulb Turbine
Flood generation	Tidal Reef	Straflo Turbine	Archimedes Screw
Bi-direction generation	Tidal Fence		Gyro
Pumping			Counter Rotating
Double Basin			

The Archimedes Screw design has the ability to operate with varying heads and range of flows while providing efficient pumping at relatively low running costs [77]. The Bay of Fundy in Canada has the world's largest tidal range [78]. Despite this potential energy, the only tidal station that exists in Canada is the Annapolis Tidal Hydroelectric Generating Station [79], however, after recent requirements imposed by Canada's Department of Fisheries and Oceans [80] due to marine impacts, the station is likely to be permanently closed [81].

2.4 Solar Power

2.4.1 Introduction

Solar power is an unbounded source of energy largely harnessed through either thermal or photonic conversion [82], see Figure 2.17. The current worldwide energy production through solar is less than 1% and less than 10% in relation to total renewable energy production. However, the potential of solar energy is as high as eighty times the current solar energy production [57].

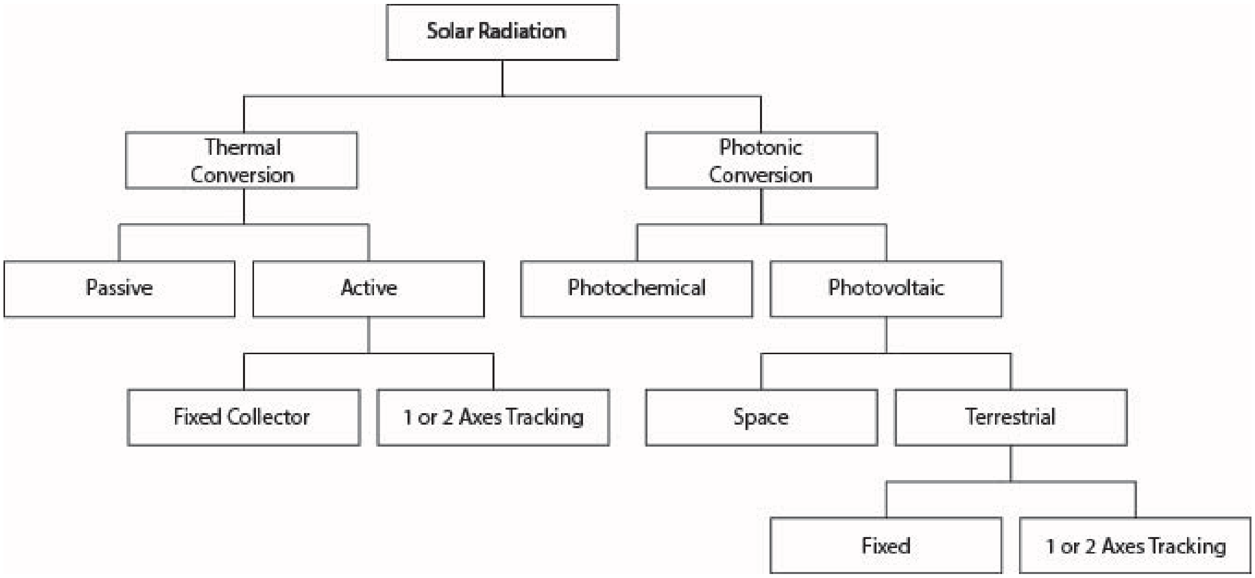

Figure 2.12: Solar radiation conversion types [83]

Despite its low market share of energy production, the current production of solar PV modules is significantly higher than production thirty years ago, resulting in a significant cost/module reduction [84]. While there is plentiful research into different types of PV cells reaching efficiencies as high as 34.1%, silicon solar cells make up approximately 95% of PV modules worldwide at an efficiency of up to 18% [82]. However, these efficiencies are improved at lower temperatures by as much as 0.5% per degree less than 25°C [85]. The current categorization of PV generation can be seen in Table 2.5.

Table 2.5: Photovoltaic generation categories [86]

First Generation Wafer-Based	Second Generation Thin-Film	Third Generation Organic
c-Si	a-Si	Perovskite
Mono-Si	a-Si:H	Dye-sensitised
Multi-Si	μ-Si	CZTS
III-V Single Junctions	CdTe	Organic
	CIGS	Polymer
	CdS	Quantum Dot
		Multi-Junction

Moreover, thermal solar power has increased substantially in capacity over the past thirty years with a similar global capacity to that of PV [87]. As seen in Table 2.5, thermal solar conversion can be divided into two types – passive and active. Passive includes thermal collectors such as greenhouses and thermosyphon hot water collectors, whereas active includes CSP systems [83]. Although the global potential for CSP systems exceeds current global energy demand, the location for CSP systems is recommended to have an annual direct normal irradiation (DNI) of at least 2000 kWh/m^2, as seen in Figure 2.18 [88].

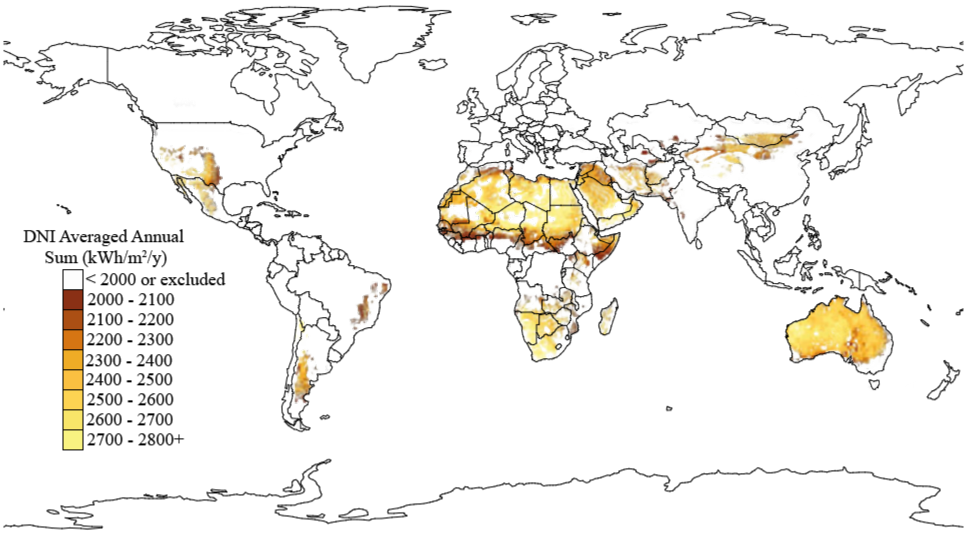

Figure 2.13: Concentrated solar power potential [88]

2.4.2 Solar power in the Canadian Arctic

From the latest photovoltaic technology status and prospects, the Canadian annual report, the total Canadian PV capacity was reported to be over 2900 MW [89]. Arctic regions, however, made up less than 0.1% of this capacity in 2017, as seen in Figure 2.19, despite significant PV potential, as seen in Figure 2.20. Consequently, the Government of Canada has made research and development of PV systems in the Arctic a priority [89]. One such area of research and development required in PV deployment in the Arctic is the reduction of snow accumulation on PV arrays, as seen in [90]. The authors of this review of a small-scale solar power plant in Adventdalen, Norway, found that while the solar array had potential, but snowdrift development posed a design challenge.

Figure 2.14: PV power capacity Canada [89]

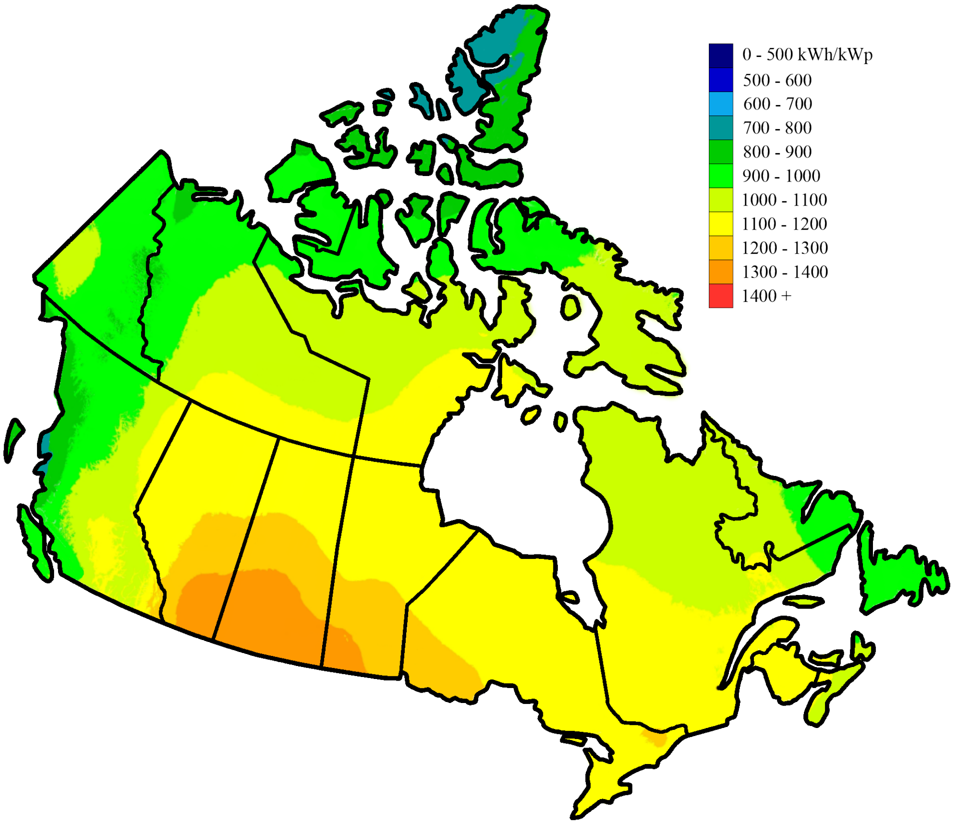

Figure 2.15: Annual photovoltaic potential [91]

While CSP potential in the Canadian Arctic is less than 2000 kWh/m2/a, there is still thermal energy potential, particularly in the summer months. In a paper reviewing the feasibility of solar energy in the Arctic, the authors explored both PV and thermal collector systems to have favourable results, with the solar thermal system producing 67% of the total yearly heating demand [85]. This study focused on an Arctic region in Narvik, Norway, with temperatures as seen in Figure 2.23. However, based on the Canadian definition of its Arctic region, north of 60° latitude [92], and in a review of climate averages in the most northern and southern weather stations of the Canadian Arctic, the feasibility of the thermal system proposed for Narvik may only be transferrable to southern Canadian Arctic regions, see Figure 2.21 and Figure 2.22. Similar reviews of solar thermal technologies in cold regions have presented positive results, albeit at seasonal temperature averages higher than the majority of the Canadian Arctic [93], [94], [95].

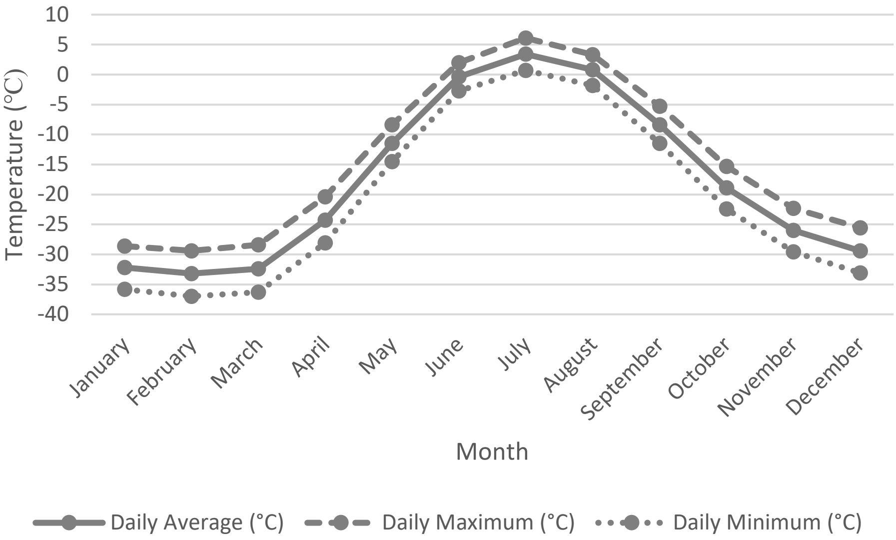

Figure 2.16: Canadian climate normals 1981-2010 station data – Alert, Nunavut [96]

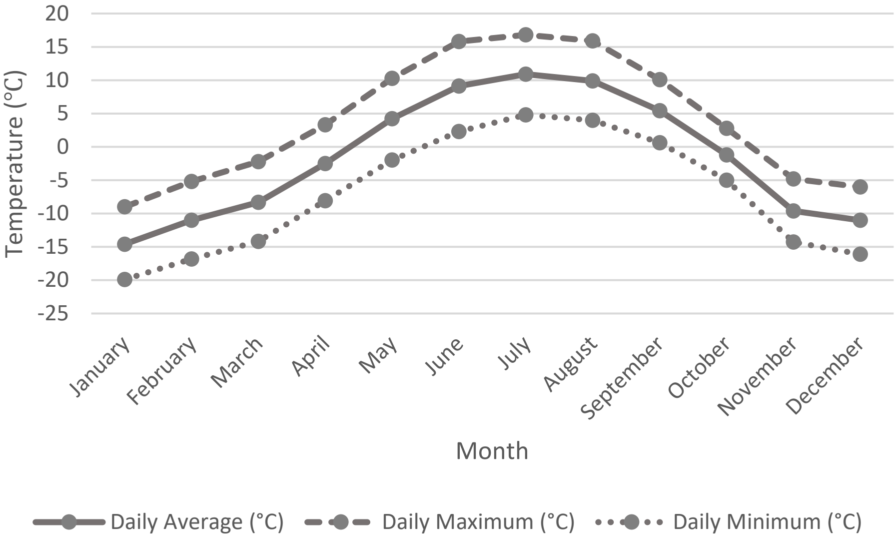

Figure 2.17: Canadian climate normals 1981-2010 station data – Blanchard River, Yukon [97]

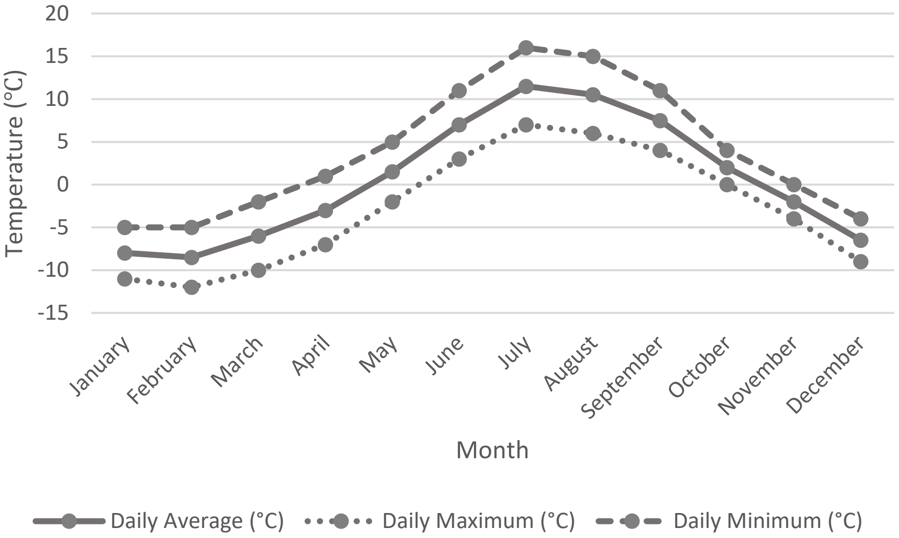

Figure 2.18: Narvik annual weather averages [98]

Although PV shows potential in the Arctic, increased costs due to the remoteness of northern communities could introduce barriers to adoption. Further research is required to understand the increased efficiencies in solar cells due to the cold climate and the impact of seasonal variations [99]. The materials used in manufacturing PV panels, recycling panels, and land used for solar farms is also of concern and should be considered prior to adoption [70].

2.4.3 Solar power energy systems

Energy through solar can be provided both thermally and electrically via PV systems. Both of these systems have potential in the Canadian Arctic, though, as previously noted, thermal systems appear to have limited potential in more northern regions. Similar to wind, one of the main problems with solar energy on its own is the variability in its energy supply [82]. Subsequent systems reviewed in this sub-section focus on overcoming this variability and have the potential of being integrated into the Canadian Arctic.

In one research paper exploring energy management using multiple energy storage systems, the authors [100] designed a system utilizing solar PV to provide electricity, as required, with additional electricity being stored in a battery storage system and hydrogen produced via electrolysis in a hydrogen storage tank, see Figure 2.24. When electrical demand exceeds the solar PV capacity, the dynamic battery energy is discharged with the hydrogen through a proton exchange membrane fuel cell (PEMFC) with slower ramp rates, providing longer term energy supply until the solar PV capacity meets the demand of the system. The authors concluded that the proposed system provide faster responses to PV variations and load demand, and the overall cost was less than the grid-connected operation.

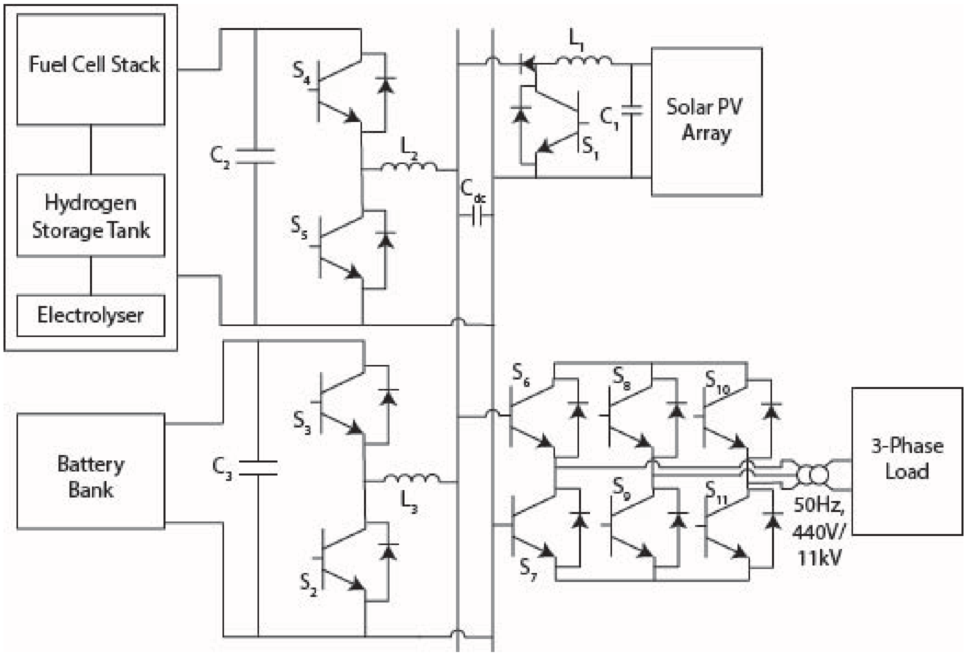

Figure 2.19: Solar PV with combined energy storage [100]

Similarly, the potential of a hybrid wind-PV system for electricity and hydrogen generation was reviewed [101]. Although the production of hydrogen was primarily for the refuelling of vehicles, the proposed configuration was found to be economically feasible through the production of excess electricity being sold back to the grid, thus increasing feasibility.

Utilizing a multiobjective optimization approach, the authors of [102] also found benefits to a hybrid wind-PV system installed in the Arctic region of Tromsø, Norway. Noted in this paper were the benefits afforded by the wind in cold regions due to increased air density in colder weather. However, the reduced solar irradiation in winter months in the Arctic emphasizes the need for the hybridization of solar energy systems in the Arctic.

Another interesting hybrid system was designed and analyzed for Arctic regions – specifically Kugaaruk, Nunavut, Canada [66]. The system proposed would provide electricity, food, fuel and desalination of water through both solar and ocean power. More specifically, the system combined OTEC, bifacial PV (BiPV) and CSP in order to achieve the objectives presented, as seen in Figure 2.25. Additionally, hydrogen was produced through electrolysis, and the CSP utilized thermal storage, as required. The system was found to have met the demands of the proposed location at 16.3% energy efficiency and 36.4% exergy efficiency [66].

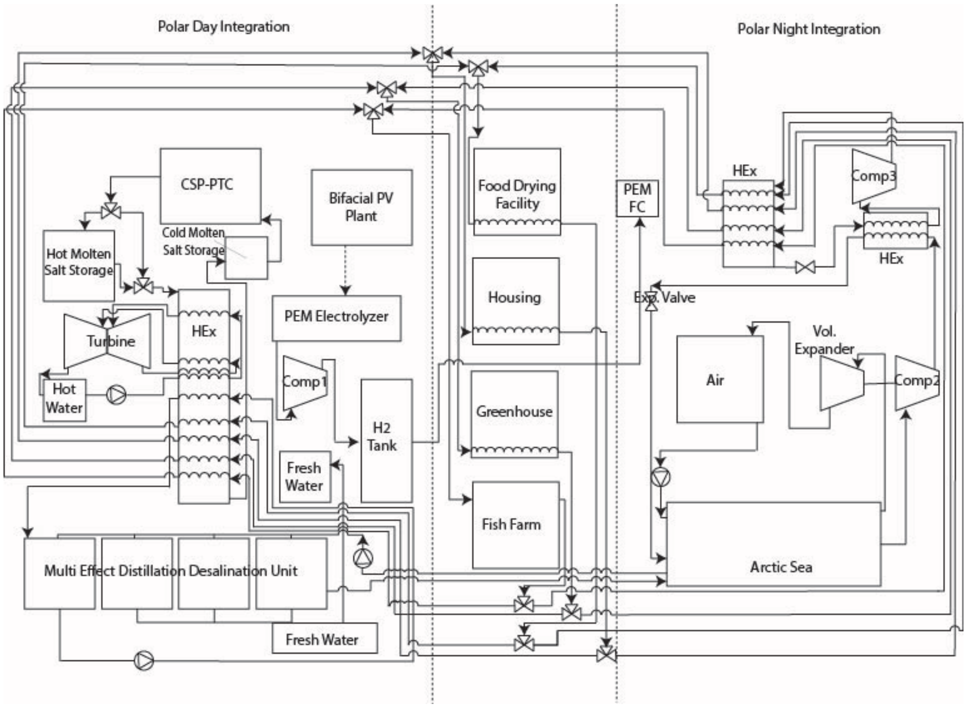

Figure 2.20: Multigenerational energy system [66]

The systems in this sub-section have predominantly looked at conventional methods of harnessing solar energy arranged in a novel way. However, there is also research in solar energy production in the early stages of development, which could also provide energy solutions in the Canadian Arctic. Examples of this include artificial photosynthesis [103] and solar energy harnessed by satellites sent to Earth via microwaves [104]. As with current solar technologies, both of these areas require further research and investment to improve their efficiency and viability.

2.5 Biomass

2.5.1 Introduction

Biomass, the conversion of non-fossil biological mass into energy, has the potential to provide a significant reduction to total GHG emissions by replacing fossil fuels [69]. However, there can be serious consequences to the use of biomass as a source of energy, including impact on food security, deforestation, water pollution, and even increasing overall net carbon emissions [105].

Biomass can generally be categorized into two unique groups; bi-product biomass and dedicated biomass. Bi-product biomass can include waste, sewage, manure or lingo-cellulosic crop residues, whereas dedicated biomass includes crops, wood and seaweeds, all of which have the potential to fulfill other human needs [69]. In a review of global biomass potential [106], current biomass models were reviewed, noting that the majority of models do not account for social, environmental and economic impacts, including food security and sustainability. It was also found that while biomass has the potential to aid in the replacement of fossil fuels, the potential availability is expected to be less than 116 EJ/year when factoring in the three pillars of sustainable energy. Furthermore, while biofuels have the potential to contribute to the reduction of GHGs, forest biofuels can also contribute to increased toxicity to humans and wildlife populations and have negative impacts on land and marine ecosystems [107].

2.5.2 Biomass in the Canadian Arctic

There is significant potential for the use of biomass in the Canadian Arctic as outlined in the Yukon Biomass Energy Strategy [108] and the Northwest Territories Biomass Energy Strategy [109]. In contrast, Nunavut does not have significant biomass potential due to the limited forested area, see Figure 2.26, and limited locally-grown food supply [110]. In a report compiled for Natural Resources Canada, biomass energy capacity was compiled across Canada for systems with a capacity between 50kW to 5MW. The total capacity equated to approximately 248 MW, eliminating up to 235,000 t CO_2 equivalent annually [111]. Overall, biomass energy in the Canadian Arctic makes up approximately 10%. However, when considering the total biomass used to heat individual homes in the Arctic, the total energy is much higher [112]. While wood makes up the primary biomass source in the Canadian Arctic, there are also other sources being exploited or have potential, including both solid waste and fish waste [110].

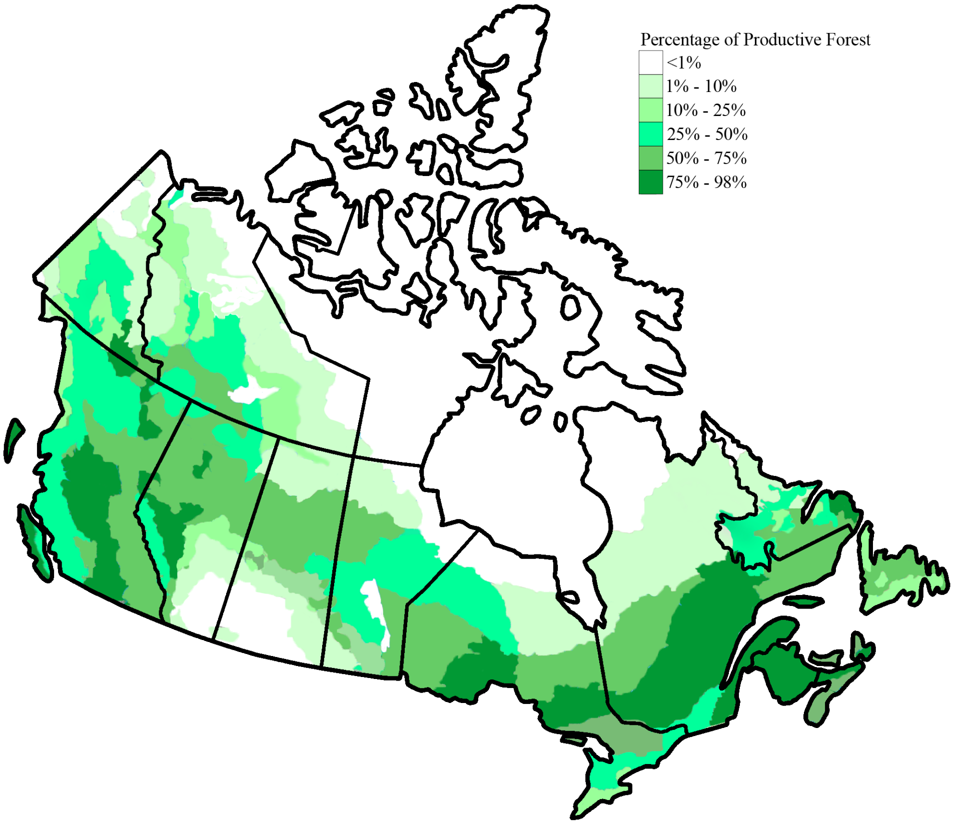

Figure 2.21: Productive forest land use [113]

2.5.3 Biomass energy systems

Similar to the aforementioned energy sources, there is a substantial body of literature on biomass and the review of potential energy systems and their performance. While not suitable for all areas of the Canadian Arctic, it is important to understand the potential systems being explored and aspects which may be incorporated into Arctic systems.

In a multigeneration system proposed [114], the researchers designed and analyzed a combined solar-biomass system to provide electricity, heating, cooling and hot water (Figure 2.27). Optimistically, the results obtained in this study served as an example of a combined biomass-solar system which was more efficient and economically viable than that of its individual counterparts, with energy and exergy efficiencies of 91% and 34.9%, respectively.

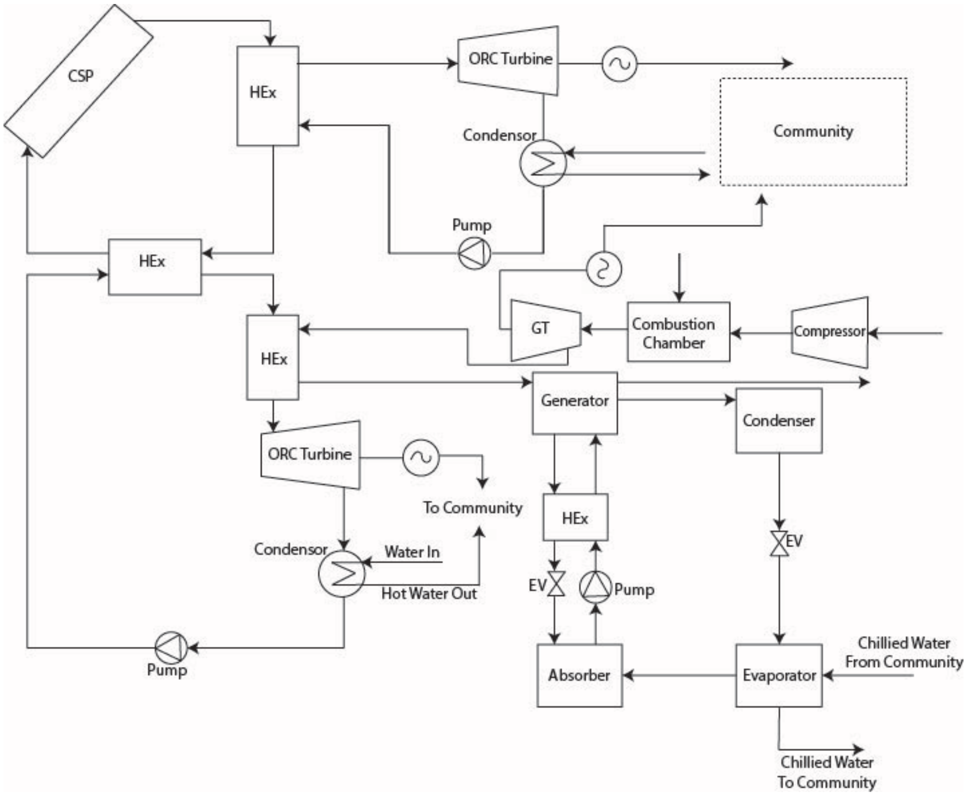

Figure 2.22: Biomass-solar multigeneration system [114]

A common theme in the literature on biomass energy generation systems was the production of hydrogen. Hydrogen production processes mentioned include gasification-rankine-absorption cycles, biomass gasification, biomass driven Rankine cycle with desalination and heating and biomass-thermochemical cycles [115], [116], [117] and [118]. Continued research in this area is vital as the sustainable generation of hydrogen is critical for the reduction of global GHG, particularly in the transportation sector [119].

2.6 Energy Storage

In order to meet the peak demands of systems, energy storage, as previously indicated, is a key component of energy systems. This is particularly relevant in systems with sporadic energy production, such as wind and solar systems. A number of systems previously reviewed contain energy storage systems, including thermal, mechanical and hydrogen storage. However, the field of energy storage contains many other purported storage solutions, see Table 2.6, including chemical, electromagnetic, and electrochemical [120].

Table 2.6: Energy storage classification [121]

Mechanical	Thermal	Chemical	Electrochemical	Electromagnetic	Biological
Pumped	Sensible	Thermochemical	Rechargeable Batteries	Capacitors	Fats
Compressed Air	Latent	Hydrogen	Flow Batteries	Super-capacitors	Chemiosmosis
Flywheel		Ammonia		Superconducting magnet	Biofuels
		SNG			
		LNG			

TES makes up a significant proportion of the literature on energy storage in cold regions. The literature also noted the high costs of energy in the north as up to 5 times the national average, citing the significance of the reduction in heating load by as much as 41.5% [122]. In another system for the heating of mines in cold climatic regions [123], a diesel generator system with TES in a rockpile collecting exhaust heat throughout summer months to supplement the heating of an underground mine was proposed. The proposed system claims potential GHG reductions of remote underground mines up to ten times. Furthermore, other studies [124] and [125] that incorporated TES into hybrid energy systems reported significant energy efficiency gains and heating cost reductions of up to 55%.

While there may be potential in mechanical and electromagnetic storage, a significant body of research does not currently exist for areas such as the Canadian Arctic. Other energy storage methods, including batteries and fuel cells, require continued research and development for viability in cold climates due to reduced performance [126].

2.7 Gaps in Literature

When developing an energy system, it is important to note that all energy systems, renewables included, have negative impacts [1]. Negative impacts from renewable energy sources can include environmental, economic and societal impacts [127], [128]. The entire life cycle of an energy system design, including manufacture, should be considered and compared with other potential energy systems to ensure the most sustainable option is chosen [129]. It is, therefore, imperative to have an understanding of the three pillars aforementioned of sustainable energy – economic, environmental and societal and the impact a proposed energy system has on each [130]. When comparing greenhouse gas emissions between the life-cycle of a renewable energy source such as solar to that of coal energy, coal is seen to produce as much as ten times emissions [131]. This alone should not dictate the choice of energy source used. While solar power may prove to have lower greenhouse gas emissions than coal, the negative economic and social impacts may outweigh the positive environmental impacts, thereby making it unsustainable [129].

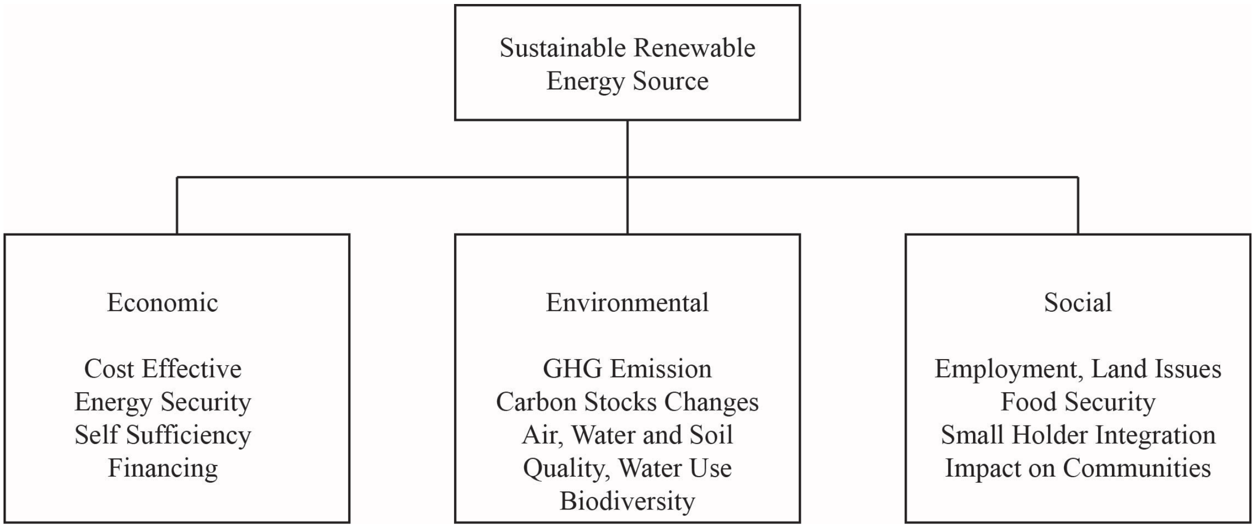

Figure 2.23: Sustainable renewable energy source criteria [129]

Current literature does not take these three pillars into account when introducing potential energy systems to the Canadian Arctic. While a number of systems discussed theoretically achieve targeted energy output, the feasibility of such systems may not be practicable due to economic and societal constraints. Furthermore, while it is understood that air-source heat pumps (ASHP) have significantly reduced performance in cold temperatures [132], the reviewed literature does not consider proposed advancements in the improvement of ASHP performance in cold regions. The following will consider the societal, environmental and economic impacts through the justification of site selection, design of proposed systems for a military base in the Canadian Arctic with the integration of an ASHP at novel performance levels for heating applications and the utilization of existing and/or proposed infrastructure where possible.

Chapter 3: Methodology

The following subsections will provide an overview of the proposed site location with justification, detail potential sustainable energy sources and the associated environmental constraints and define the design constraints of the proposed military base. Additionally, the proposed energy systems will be introduced and thermodynamically analyzed.

3.1 Proposed Location

In addition to being north of 66.5ºN (Arctic Circle), the determination for the proposed military base and associated energy system location was made based on a variety of criteria, including:

- Existing airport infrastructure
- Canadian Arctic centrality – Latitude and Longitude
- Existing seaport infrastructure
- Current and projected population
- Location proximity to major shipping routes
- Airport and seaport expansion potential
- Sustainable energy potential

According to a recent report on Canadian Arctic airports, there are approximately 42 operational airports north of 66.5ºN with runways of varying characteristics [133]. While a location with an existing paved airport is ideal, Inuvik Mike Zubko Airport is the only location to support this requirement. However, Inuvik is not a central location in the Canadian Arctic, and it is too far inland to be considered along any major shipping routes. The remaining airports were compared based on location, centrality, runway length, population of supported community and potential for expansion.

Cambridge Bay is a Hamlet located on Victoria Island with coordinates 69.1169ºN, 105.0597ºW approximately -5ºN and 5ºW off center of the Canadian Arctic. Its airport has a gravel runway with a length of 1,547m and currently supports a population of 1,766 in addition to the Canadian High Arctic Research station. According to the United States Air Force, paved runway requirements for C-5 and C-17 military aircraft are approximately 1829 m long and 45 m wide and 1220 m long and 27 m wide, respectively [134]. While Cambridge Bay is neither paved nor supports the length requirements for both aircraft, the Royal Canadian Air Force has already taken part in operations landing C-17 aircraft at multiple locations in the Canadian Arctic, including Cambridge Bay [135]. Nevertheless, as part of its infrastructure plan, the Government of Nunavut plans to upgrade Cambridge Bay airport, including lengthening and paving of the runway and expansion of the airport terminal [136]. Although Cambridge Bay does not currently have a deep water port, current literature on shipping route depths supports a potential deep water port expansion [137]. Furthermore, Cambridge Bay is located along the Northwest Passage and plans for its port expansion for small craft are also included in the Government of Nunavut infrastructure plan [136].

3.2 Energy System Design Constraints

3.2.1 Environmental constraints

A corporation of the Government of Nunavut, the Qulliq Energy Corporation, provides electricity to residents in Cambridge Bay with electricity through a diesel power plant. In order to meet growing demands, a new diesel plant is being proposed capable of integrating renewable energy sources [160]. In general, geothermal potential in Nunavut is low when considering current technological drilling constraints and limited heat flow maps [161]. Due to a lack of data for Cambridge Bay, geothermal energy is not a suitable option at this time. Alternatively, wind, marine, solar and biomass all show varying degrees of suitability.

Wind data provided by [138] for Cambridge Bay indicates an annual average speed of approximately 5.4 m/s classing the wind potential in the poor to marginal category according to Table 2.2. However, as it is standard practice to measure wind speed at 10 m above ground, the true wind potential at turbine height is greater [139]. An approximate average speed at potential turbine heights can be found logarithmically according to Equation (3.1) [140] and can be seen in Figure 3.2.

$$u_2 = u_1 \frac{\ln(\frac{z_2}{z_0})}{\ln(\frac{z_1}{z_0})} \tag{3.1}$$

Where u_2 is the wind speed at height z_2, u_1 is the known wind speed at height z_1, and z_0 is the surface roughness. Roughness at Cambridge Bay station is estimated at 0.005 m as typically near airports [141].

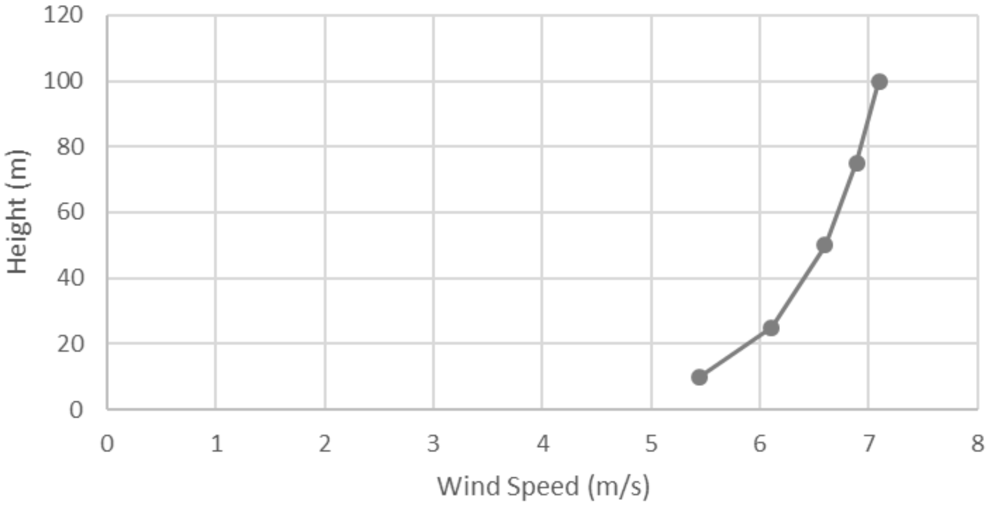

Figure 3.1: Annual average wind speed - Cambridge Bay, NU

As previously discussed, salinity gradients in northern estuaries could also be harnessed for power generation [142]. In Cambridge Bay, the waters of Freshwater Creek run into the Arctic with a maximum discharge rate of approximately 37 m^3/s [143] and has the potential to provide osmotic power; however, it is limited to the months of June and October due to the formation of ice, see Figure 3.3 [143].

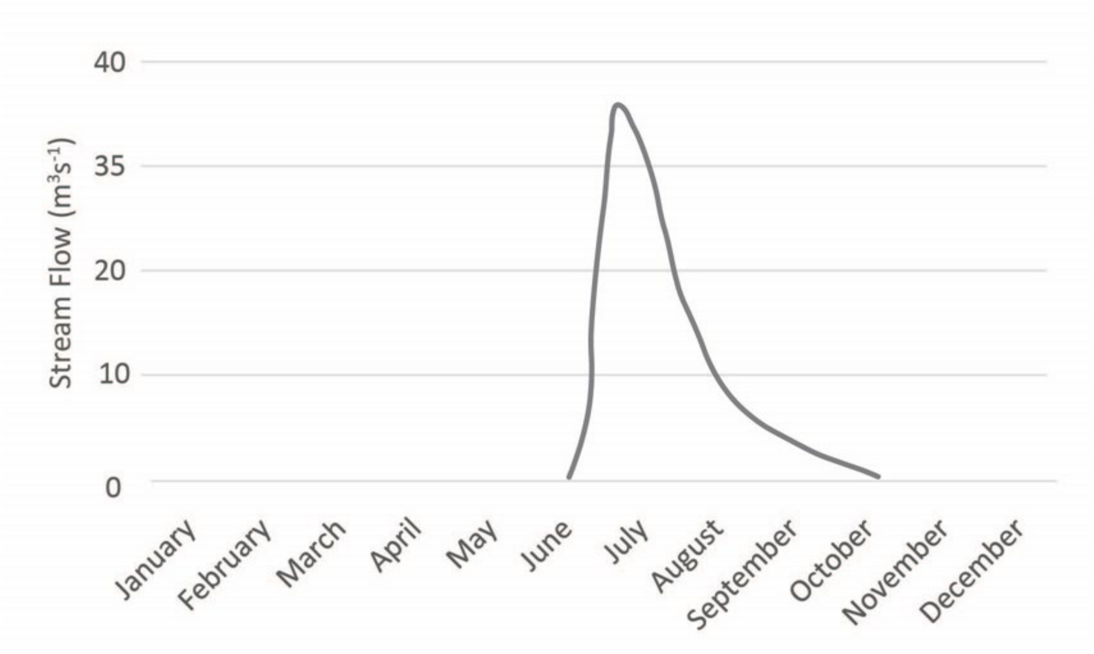

Figure 3.2: Average discharge for Fresh Water creek [143]

While there may be potential to produce energy through osmotic power using Freshwater Creek for five months of the year, consideration should take into account Freshwater Creek is also used to harvest Arctic Char, and the impact of a power plant may have negative consequences on stock [144].

Similarly, solar power in the Arctic is limited to certain times of the year due to the lack of sunlight through the winter months. Other barriers to adoption also include snow accumulation and the initial cost of installation due to the remoteness of northern communities. For the area of Cambridge Bay specifically, the solar radiation profile through the year can be seen in Figure 3.4:

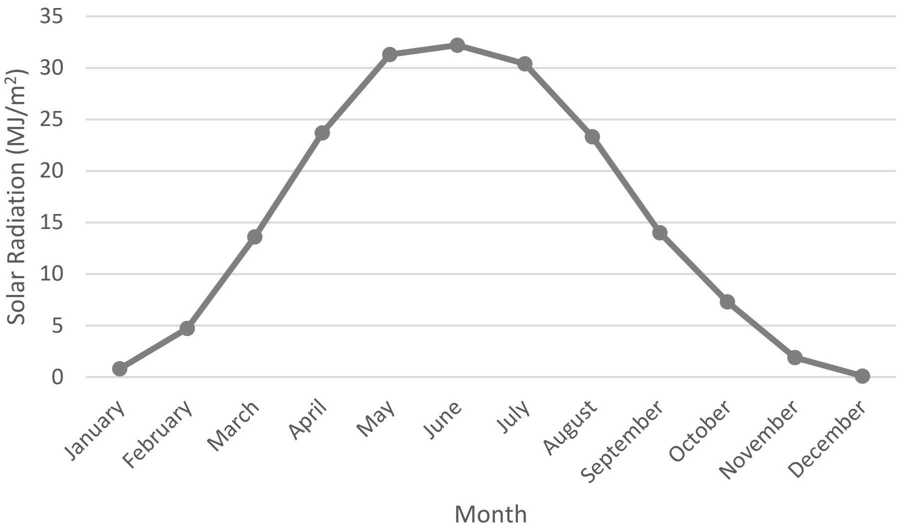

Figure 3.3: Solar radiation (MJ/m^2) for Cambridge Bay, Nu [138]

While Nunavut lacks the natural wood biomass other Canadian Arctic territories possess, as seen in Figure 2.26, other potential biofuels exist, including waste and animal bi-products. Solid waste in Cambridge Bay is currently dumped at a local landfill to be subsequently burned when there is a north or west wind [136]. The Government of Nunavut is currently seeking to enhance their incineration system using a thermal oxidation system (TOS) in order to reduce harmful off-gases. In conjunction with this approach, with 5000 kg of waste and 1840 kg sewage per day currently produced by Cambridge Bay and with the addition of waste generated on a potential military base, there is potential to utilize the thermal energy from the incinerator to produce usable energy for the base and/or community [145].

Other environmental constraints impacting the system design for Cambridge Bay include snowfall, humidity and temperature. This data for Cambridge Bay provided by [138] can be seen in Figure 3.5, Figure 3.6 and Figure 3.7

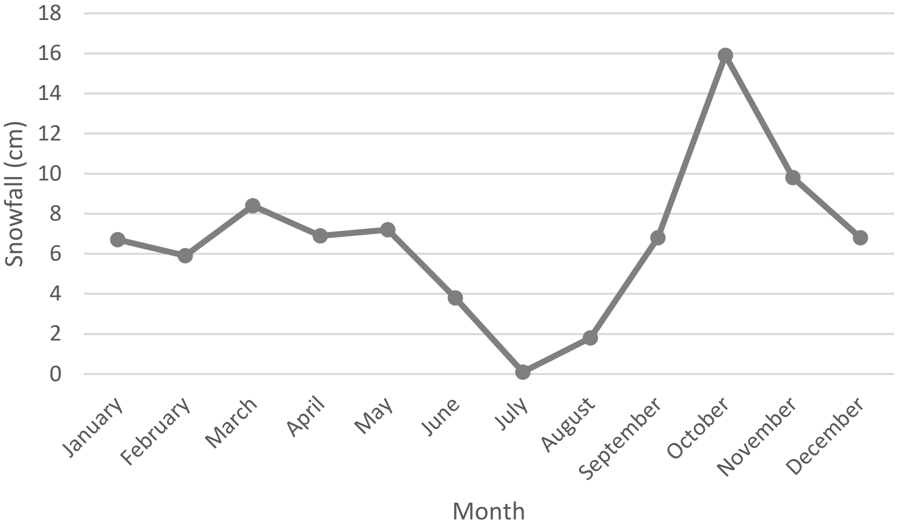

Figure 3.4: Average snowfall (cm) - Cambridge Bay, Nu [138]

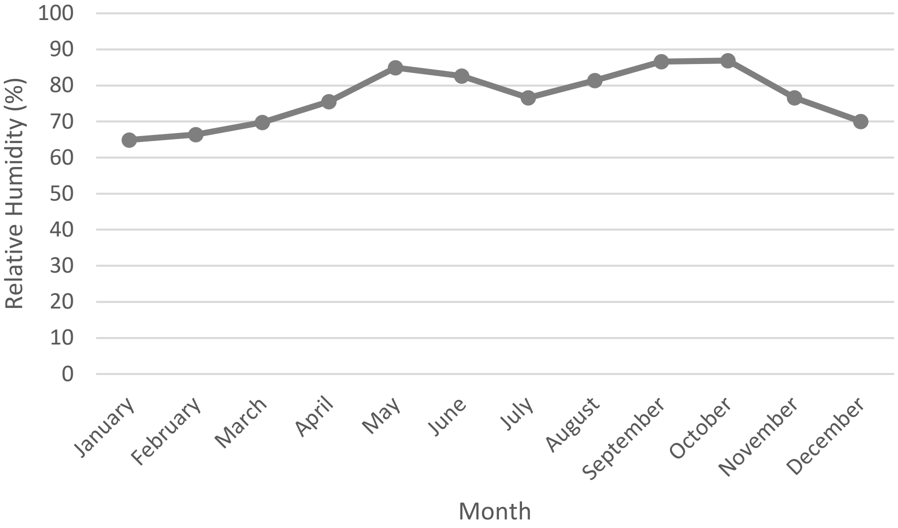

Figure 3.5: Average relative humidity (%) - Cambridge Bay, Nu [138]

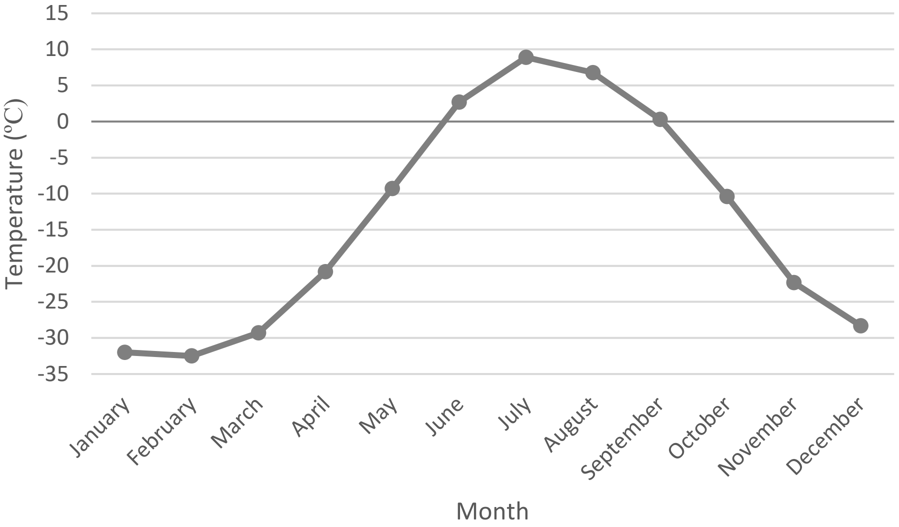

Figure 3.6: Average temperature (ºC) - Cambridge Bay, Nu [138]

3.2.2 Military base constraints

The proposed military base for Cambridge Bay, as described in 1.3 Objectives, includes similar requirements set by the DND for the Nanisivik Naval Facility while also supporting up to 1000 military personnel to support northern operations. Support includes provision for heating, electricity, farming and waste management.

The executive summary for the Nanisivik Naval Facility defined the scope of the project at a high level and included upgrades of the existing deep-water wharf, cargo storage, bulk liquid storage and associated infrastructure, storage building (unheated), helipad, outdoor lighting for the wharf and liquid storage location and power generation to support the requirements [146]. Relevant project specific information can be seen in Table 3.1 [147].

Table 3.1: Nanisivik naval facility original defined requirements [147]

Projected Land Size	43.7 hectares	
Projected Personnel	4 people	
Projected Waste Volume	14 m^3/year	
Naval Distillate	7.5 million L	Two tanks
Diesel	100,000 L	Two tanks
Aviation Fuel	3,000 L	15 Drums
Wharf	Upgrade to existing infrastructure	
Storage Building	Pre-fab unheated steel frame structure	
Potable Water	Water supply from community	
Wastewater	Waste management by local community	
Solid Waste	Compacted, shipped and disposed in southern Canada	
Fire Protection	Passive	

Additionally, to support the requirements of 1,000 military personnel in the area, housing and greenhouses are required. For the purposes of heat-load calculations, the housing proposed for the military base in Cambridge Bay is two-floor row housing of approximately 100m^2 of 1,000 units. Greenhouses proposed support up to 10% of food requirements utilizing conventional hydroponics vertical farming. Proposed greenhouses are of Quonset hut design for ease of manufacture and assembly on-site.

3.2.3 Heating load

The heating load of the proposed housing is calculated using Equation (3.2) in accordance with AHRI Standard 210/240 [148]:

$$BL_{tj} = \left\{\frac{t_{zl}-t_j}{t_{zl}-t_{OD}}\right\} \cdot C_x \cdot \dot{q}_{AFull} \tag{3.1}$$

In Eq. 3.2, t_j is the outdoor bin temperature, t_{zl} is the zero-load temperature in accordance with the climate region, t_{OD} is the outdoor design temperature in accordance with the climate region, C_x is the slope factor in accordance with the climate region and $\dot{\boldsymbol{q}}_{\boldsymbol{AFull}}$ is the cooling capacity at 95ºF – assumed at 20,000 BTU/1000ft^2.

The heating load of the proposed greenhouse coverage is calculated using Equations (3.3) and (3.4), where Equation (3.3) is the surface area of the Quonset hut structure:

$$A = \frac{\pi}{2}(A * B) + \pi\left(\frac{A^2}{4}\right) \tag{3.2}$$

In Eq. 3.3, A and B are the length and width of the Quonset hut greenhouse structure.

$$\mathrm{Q} = \mathrm{U} * \mathrm{A} * \Delta\mathrm{T} \tag{3.3}$$

In Eq. 3.4, U is the heat transfer coefficient of the greenhouse – assumed at 0.7 BTU/hr ft^2 ºF, A is the surface area of the greenhouse given by Equation (3.3) and ΔT is the difference in temperature between inside and outside air.

3.2.4 Electrical load

According to Statistics Canada, the average household uses approximately 11,000 kWh of electricity per year [149]. It is assumed housing for the base will consume this average per house per year. Additionally, to account for electricity of ancillaries including pumping, facility buildings, street lighting and farming, it is assumed housing electrical demand makes up 20% of overall electrical demand based on Ontario's total electricity consumption [150].

3.2.5 Water requirements

According to Statistics Canada, the total potable water utilized per person (residential and ancillaries) was approximately 0.411m^3/day [151]. Therefore, 0.411m^3/day is the expected usage rate of water per person for the proposed military base requiring desalination.

3.3 Proposed System Description

The proposed system for the aforementioned military base in Cambridge Bay is shown in Figure 3.8. This system is co-powered by both wind and a TOS waste management system to achieve the necessary electrical, fresh water, hot water and heating demands and includes energy provisions for approximately 10% of the overall food supply required. Due to the stochastic nature of wind power generation, electricity will be stored chemically through novel atmospheric humidity electrolysis to reduce desalination requirements [152]. When required, hydrogen will be reconverted into electricity through a solid oxide fuel cell (SOFC) to support the base. The TOS system utilizes the waste heat of the TOS process to power a steam turbine and has been scaled based on the current population of Cambridge Bay in addition to the proposed base. Heating is accomplished via a heat exchanger with an ASHP with a compressor powered by electricity generated in the system. The working fluid proposed for the ASHP is R410a in order to achieve system constraints. Fresh water for the community and heating requirements is produced via an osmosis desalination plant to reduce community heating loads.

3.3.1 Thermal oxidation system

TOS waste management has been proposed by the Government of Nunavut for Cambridge Bay. This system seeks to utilize the waste heat of the TOS to generate electricity. This system is made up of four state points, a steam turbine, a condenser and a pump. At state #1, water has been superheated by the TOS to produce steam to enter the turbine and exits at state #2, producing electricity for the overall system at state #32. The now liquid-gas mixture at state #2 enters a condenser which releases the excess heat to the atmosphere before returning to liquid water at state #3. Pressure is then increased through pump #1, and the water is returned to the TOS to be heated to approximately 350 ℃. Overall, the system has been designed and analyzed based on approximate solid waste potential from a population of 3000 people.

3.3.2 Desalination

A reverse osmosis membrane desalination plant has been chosen to support the system design as it is currently the most frequent technique being used worldwide, does not require pre-heating and can accommodate very cold temperatures [153], [154]. The system and flow rates have been designed to accommodate a 60% freshwater recovery rate, 10 ℃ seawater inlet stream and operating pressure of approximately 5.5mPa based on [154]. The desalination plant is produced by state #37, at approximately 8.2kWh/m^3. Seawater at state #10 is drawn into the desalination plant at state #11 by way of pump #3, which increases the inlet pressure required for reverse osmosis. Brine is rejected from the plant at state #12 and sent to pump #2, where it is discarded at state #13. Freshwater is produced at state #14 and pumped to the freshwater holding tank by pump #5 at state #15. Water to be heated is pumped from state #18 by pump #6 through state #19 to the fuel cell to state #20 where it gains heat when the fuel cell is active. State #20 proceeds to the ASHP heat exchanger, then exits at state #21 to the hot water storage tank. Hot water is then pumped from state #22 to state #23 through pump #9 to provide hot water for the base. Wastewater is sent through states #24 and #25 via pump #10 to a liquid waste management facility, where a purified liquid is rejected at states #26 and #27 and pump #4.

3.3.3 Heating

A closed loop heating circuit has been used to provide district heating to the community. This loop starts at state #28 where its pressure is increased by pump #7 to standard municipal pressure guidelines. It then passes through the fuel cell from states #29 to #30 where it gains heat when the fuel cell is active. State #30 proceeds to the ASHP heat exchanger and then exits at state #31 to provide the community heating requirements.

3.3.4 Air-source heat pump

An ASHP has been used to provide district heating to the base. An assumed coefficient of performance of 2.0 has been used in the design and analysis of this system as a result of the improvements in this technology for cold weather applications. The ASHP is made up of a compressor, condenser (heat exchanger), expansion valve and evaporator. R410a enters the compressor at state #8 and compresses the refrigerant as a superheated gas at state #5. The refrigerant then goes through the heat exchanger and rejects heat to the water supply for heating the base and returns to saturated liquid at state #6. The refrigerant enters the expansion valve and exits at state #7 as a liquid-gas mixture which enters the evaporator absorbing heat from the atmosphere and exits back to state #8. The compressor is powered at state #9 through electricity produced in the system.

3.3.5 Energy storage

The chemical energy storage for this system is comprised of an electrolyzer, hydrogen storage, oxygen storage and a SOFC fuel cell. The electrolyzer produces hydrogen and oxygen via electricity at state #34 and atmospheric humidity. Hydrogen is produced at state #35 and oxygen at state #36 and stored in respective storage tanks. State #37 passes hydrogen through a SOFC fuel cell to reconvert the hydrogen back to electricity for the system. When the fuel cell is operating, the heat loss is absorbed into the freshwater supply for heating at state #20. Electrolysis efficiency is estimated at approximately 60%, and fuel cell efficiency at 60%, with an increase to 90% when coupled with heating the freshwater heating fluid.

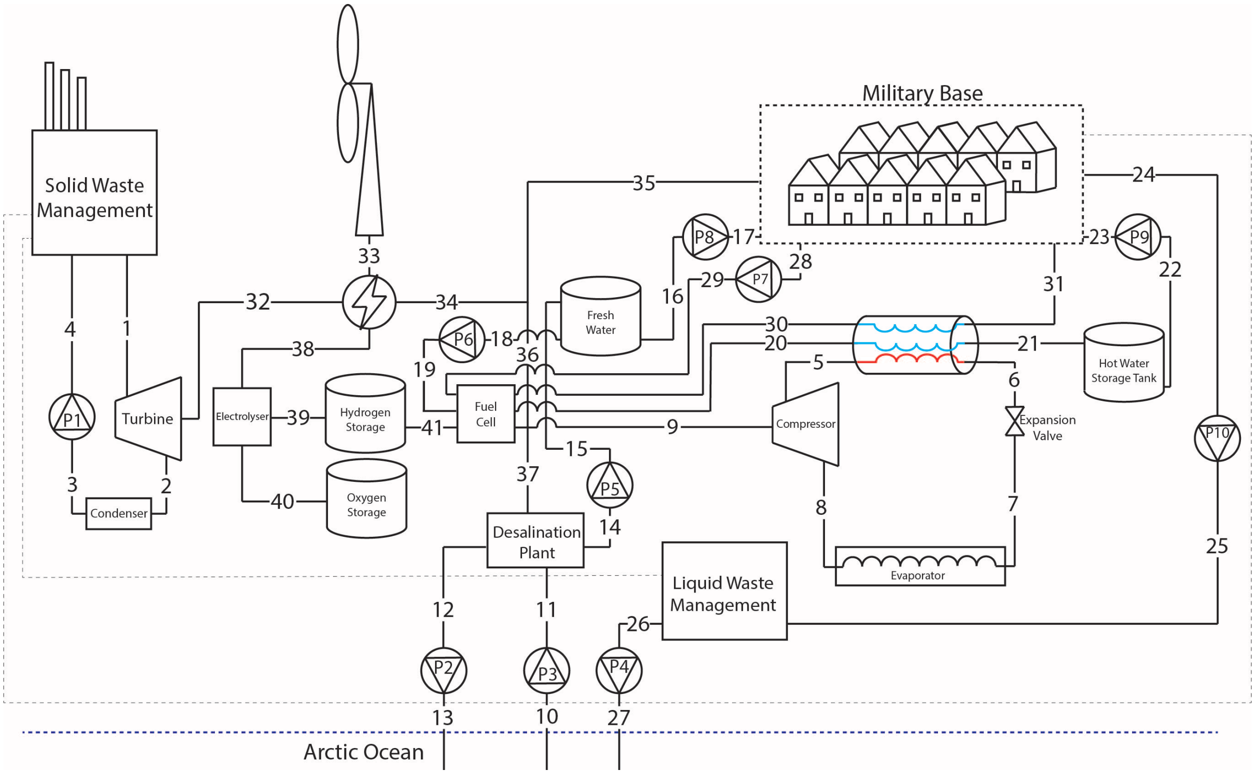

Figure 3.7: Proposed energy system diagram and state points

3.4 Thermodynamic Analysis

The following sections describe the thermodynamic analysis of the proposed system in accordance with the first and second laws of thermodynamics. This analysis is described through mass balance, energy balance, entropy balance and exergy balance equations. Numerical subscripts are aligned with state points, as shown in Figure 3.7. Efficiency calculations are also described for the relevant system components as well as the overall energy and exergy efficiencies and relevant COPs. Additionally, a list of assumptions that were used in the design and analysis of the system will be presented. Figure 3.8 provides a flow chart of the methodology used to conduct the overall thermodynamic analysis.

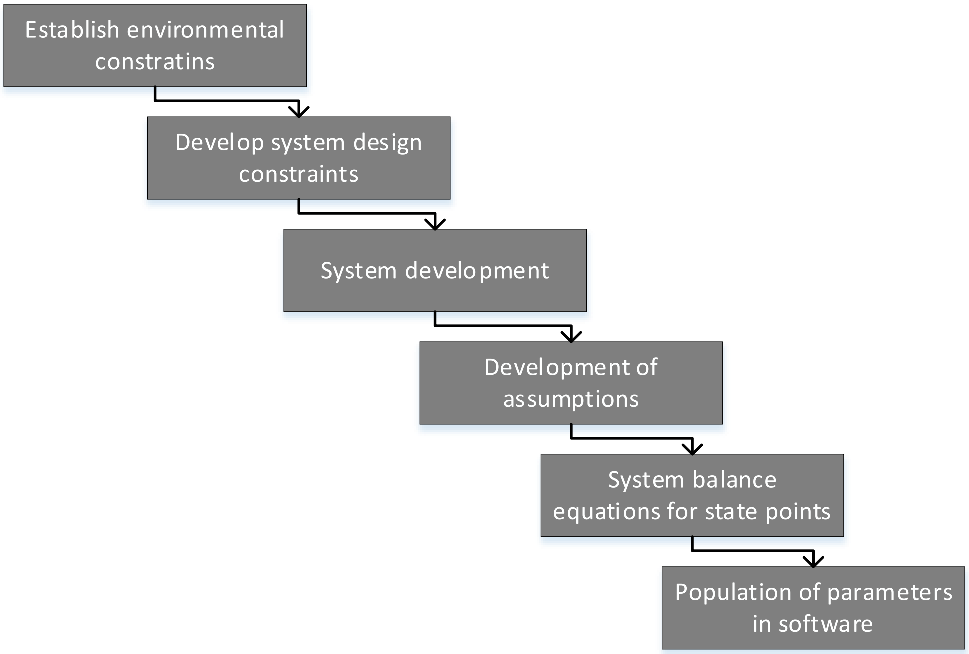

Figure 3.8: Thermodynamic analysis flow chart

3.4.1 System assumptions

Assumptions used in the development and analysis of the proposed system are presented below:

- All parts of the system are working under steady state conditions.
- All parts of the system are adiabatic except for the condensers, evaporator and fuel cell. All heat loss through pumps, turbines, compressors, piping, etc., is considered negligible.
- Turbine isentropic efficiency is estimated at approximately 87%.
- Electrolysis efficiency is estimated at approximately 70%.
- SOFC fuel cell efficiency is estimated at approximately 60%.
- SOFC heat capture increases SOFC to 90% efficient
- Sea water temperature is approximately 10°C throughout the year.

3.4.2 Turbine

Mass Balance Equation:

$$\dot{m}_1 = \dot{m}_2 \tag{3.5}$$

Energy Balance Equation:

$$\dot{m}_1 h_1 = \dot{m}_2 h_2 + \dot{W}_{Turb} \tag{3.6}$$

Where $\dot{W}_{Turb}$ is the power output of the steam turbine in the TOS system and where:

$$\dot{W}_{Turb} = \dot{m}(h_1 - h_2) \tag{3.7}$$

Entropy Balance Equation:

$$\dot{m}_1 s_1 + \dot{S}_{gen\_turb} = \dot{m}_2 s_2 \tag{3.8}$$

Where $\dot{S}_{gen\_turb}$ is the entropy generation rate of the steam turbine in the TOS system.

Exergy Balance Equation:

$$\dot{m}_1 ex_1 = \dot{m}_2 ex_2 + \dot{W}_{Turb} + \dot{E}x_{Dest\_Turb} \tag{3.9}$$

Where $\dot{E}x_{Dest\_Turb}$ is the exergy destruction rate of the steam turbine in the TOS system.

3.4.3 Condenser

Mass Balance Equation:

$$\dot{m}_2 = \dot{m}_3 \tag{3.10}$$

Energy Balance Equation:

$$\dot{m}_2 h_2 = \dot{m}_3 h_3 + \dot{Q}_{Cond} \tag{3.11}$$

Where $\dot{Q}_{Cond}$ is the heat loss of the condenser.

Entropy Balance Equation:

$$\dot{m}_2 s_2 + \dot{S}_{gen\_cond} = \dot{m}_3 s_3 + \frac{\dot{Q}_{Cond}}{T_0} \tag{3.12}$$

Where $\dot{S}_{gen\_cond}$ is the entropy generation rate of the condenser and T_0 is the ambient temperature and where:

$$\dot{Q}_{Cond} = \dot{m}(h_2 - h_3) \tag{3.13}$$

Exergy Balance Equation:

$$\dot{m}_2 ex_2 = \dot{m}_3 ex_3 + \dot{E}x_{Q\_Cond} + \dot{E}x_{Dest\_Cond} \tag{3.14}$$

Where $\dot{E}x_{Q\_Cond}$ is the exergy of the heat loss of the condenser and $\dot{E}x_{Dest\_Cond}$ is the exergy destruction rate of the condenser.

3.4.4 System pumps

Mass Balance Equation:

$$\dot{m}_x = \dot{m}_y \tag{3.15}$$

Energy Balance Equation:

$$\dot{m}_x h_x + \dot{W}_{Pump\_n} = \dot{m}_y h_y \tag{3.16}$$

Where $\dot{W}_{Pump\_n}$ is the input of power for pumps in the system and where:

$$\dot{W}_{Pump\_n} = \dot{m}(h_y - h_x) \tag{3.17}$$

Entropy Balance Equation:

$$\dot{m}_x s_x + \dot{S}_{gen\_pump\_n} = \dot{m}_y s_y \tag{3.18}$$

Where $\dot{S}_{gen\_pump\_n}$ is the entropy generation of the pumps in the system.

Exergy Balance Equation:

$$\dot{m}_x ex_x + \dot{W}_{Pump\_n} = \dot{m}_y ex_y + \dot{E}x_{Dest\_pump\_n} \tag{3.19}$$

Where $\dot{E}x_{Dest\_pump\_n}$ is the exergy destruction rate of pumps in the system.

3.4.5 Desalination plant

Mass Balance Equation:

$$\dot{m}_{11} = \dot{m}_{14} + \dot{m}_{12} \tag{3.20}$$

Energy Balance Equation:

$$\dot{m}_{11} h_{11} + \dot{W}_{Osmosis} = \dot{m}_{14} h_{14} + \dot{m}_{12} h_{12} \tag{3.21}$$

Where $\dot{W}_{Osmosis}$ is the power input to the desalination system.

Entropy Balance Equation:

$$\dot{m}_{11} s_{11} + \dot{S}_{gen\_Osmosis} = \dot{m}_{14} s_{14} + \dot{m}_{12} s_{12} \tag{3.22}$$

Where $\dot{S}_{gen\_Osmosis}$ is the entropy generation rate of the desalination system.

Exergy Balance Equation:

$$\dot{m}_{11} ex_{11} + \dot{W}_{Osmosis} = \dot{m}_{14} ex_{14} + \dot{m}_{12} ex_{12} + \dot{E}x_{Dest\_Osmosis} \tag{3.23}$$

Where $\dot{E}x_{Dest\_Osmosis}$ is the exergy destruction rate of the desalination system.

3.4.6 Electrolyser

Mass Balance Equation:

$$\dot{m}_H + \dot{W}_{38} = \dot{m}_{39} + \dot{m}_{40} \tag{3.24}$$

Energy Balance Equation:

$$\dot{m}_H h_H + \dot{W}_{38} = \dot{m}_{39} h_{39} + \dot{m}_{40} h_{40} \tag{3.25}$$

Entropy Balance Equation:

$$\dot{m}_H s_H + \dot{S}_{gen\_Electrolyser} = \dot{m}_{39} s_{39} + \dot{m}_{40} s_{40} \tag{3.26}$$

Where $\dot{S}_{gen\_Electrolyser}$ is the entropy generation of the electrolyser.

Exergy Balance Equation:

$$\dot{m}_H ex_H + \dot{W}_{38} = \dot{m}_{39} ex_{39} + \dot{m}_{40} ex_{40} + \dot{E}x_{Dest\_Electrolyser} \tag{3.27}$$

Where $\dot{E}x_{Dest\_Electrolyser}$ is the exergy destruction rate of the electrolyser.

3.4.7 SOFC fuel cell

Mass Balance Equation:

$$\dot{m}_{41} + \dot{m}_{19} + \dot{m}_{29} = \dot{m}_{20} + \dot{m}_{30} + \dot{W}_{SOFC} \tag{3.28}$$

Where $\dot{W}_{SOFC}$ is the power output of the SOFC fuel cell.

Energy Balance Equation:

$$\dot{m}_{41}h_{41} + \dot{m}_{19}h_{19} + \dot{m}_{29}h_{29} = \dot{m}_{20}h_{20} + \dot{m}_{30}h_{30} + \dot{W}_{SOFC} \tag{3.29}$$

Entropy Balance Equation:

$$\dot{m}_{41}s_{41} + \dot{m}_{19}s_{19} + \dot{m}_{29}s_{29} + \dot{S}_{gen\_SOFC} = \dot{m}_{20}s_{20} + \dot{m}_{30}s_{30} \tag{3.30}$$

Where $\dot{S}_{gen\_SOFC}$ is the entropy generation rate of the SOFC fuel cell.

Exergy Balance Equation:

$$\dot{m}_{41}h_{41} + \dot{m}_{19}h_{19} + \dot{m}_{29}h_{29} = \dot{m}_{20}h_{20} + \dot{m}_{30}h_{30} + \dot{W}_{SOFC} + \dot{E}x_{Dest\_SOFC} \tag{3.31}$$

Where $\dot{E}x_{Dest\_SOFC}$ is the exergy destruction rate of the SOFC fuel cell.

3.4.8 Compressor

Mass Balance Equation:

$$\dot{m}_8 = \dot{m}_5 \tag{3.32}$$

Energy Balance Equation:

$$\dot{m}_8h_8 + \dot{W}_9 = \dot{m}_5h_5 \tag{3.33}$$

$$\eta_{comp} = \frac{h_{5,s} - h_8}{h_5 - h_8} \tag{3.34}$$

Where $\dot{W}_9$ is the electrical power provided to the compressor and η_{comp} is the isentropic efficiency of the compressor with $h_{5,s}$ representing enthalpy under ideal compressor conditions.

Entropy Balance Equation:

$$\dot{m}_8 s_8 + \dot{S}_{gen\_comp} = \dot{m}_5 s_5 \tag{3.35}$$

Where $\dot{S}_{gen\_comp}$ is the entropy generation rate of the compressor.

Exergy Balance Equation:

$$\dot{m}_8 ex_8 + \dot{W}_{comp} = \dot{m}_5 ex_5 + \dot{E}x_{Dest\_comp} \tag{3.36}$$

Where $\dot{W}_{comp}$ work input to the compressor and $\dot{E}x_{Dest\_comp}$ is the exergy destruction rate of the compressor.

3.4.9 Evaporator

Mass Balance Equation:

$$\dot{m}_7 = \dot{m}_8 \tag{3.37}$$

Energy Balance Equation:

$$\dot{m}_7 h_7 + \dot{Q}_{Evap} = \dot{m}_8 h_8 \tag{3.38}$$

Where $\dot{Q}_{Evap}$ is the heat transfer rate through the evaporator and where:

$$\dot{Q}_{Evap} = \dot{m}(h_8 - h_7) \tag{3.39}$$

Entropy Balance Equation:

$$\dot{m}_7 s_7 + \dot{S}_{gen\_Evap} + \frac{\dot{Q}_{Evap}}{T_0} = \dot{m}_8 s_8 \tag{3.40}$$

Where $\dot{S}_{gen\_Evap}$ is the entropy generation rate of the evaporator.

Exergy Balance Equation:

$$\dot{m}_7 ex_7 + \dot{E}x_{Q\_Evap} = \dot{m}_7 ex_7 + \dot{E}x_{Dest\_Evap} \tag{3.41}$$

Where $\dot{E}x_{Q\_Evap}$ is the exergy of the heat transfer rate of the evaporator and $\dot{E}x_{Dest\_Evap}$ is the exergy destruction rate of the evaporator.

3.4.10 Heat exchanger

Mass Balance Equation:

$$\dot{m}_5 + \dot{m}_{20} + \dot{m}_{30} = \dot{m}_6 + \dot{m}_{21} + \dot{m}_{31} \tag{3.42}$$

Energy Balance Equation:

$$\dot{m}_5 h_5 + \dot{m}_{20} h_{20} + \dot{m}_{30} h_{30} = \dot{m}_6 h_6 + \dot{m}_{21} h_{21} + \dot{m}_{31} h_{31} \tag{3.43}$$

Entropy Balance Equation:

$$\dot{m}_5 s_5 + \dot{m}_{20} s_{20} + \dot{m}_{30} s_{30} + \dot{S}_{gen\_HEX} = \dot{m}_6 s_6 + \dot{m}_{21} s_{21} + \dot{m}_{31} s_{31} \tag{3.44}$$

Where $\dot{S}_{gen\_HEX}$ is the entropy generation rate of the heat exchanger.

Exergy Balance Equation:

$$\dot{m}_5 ex_5 + \dot{m}_{20} ex_{20} + \dot{m}_{30} ex_{30} = \dot{m}_6 ex_6 + \dot{m}_{21} ex_{21} + \dot{m}_{31} ex_{31} + \dot{E}x_{Dest\_HEX} \tag{3.45}$$

Where $\dot{E}x_{Dest\_HEX}$ is the exergy destruction rate of the heat exchanger.

3.4.11 Expansion valve

Mass Balance Equation:

$$\dot{m}_6 = \dot{m}_7 \tag{3.46}$$

Energy Balance Equation:

$$\dot{m}_6 h_6 = \dot{m}_7 h_7 \tag{3.47}$$

Entropy Balance Equation:

$$\dot{m}_6 s_6 + \dot{S}_{gen\_Exp} = \dot{m}_7 s_7 \tag{3.48}$$

Where $\dot{S}_{gen\_Exp}$ is the entropy generation rate of the expansion valve.

Exergy Balance Equation:

$$\dot{m}_6 ex_6 = \dot{m}_7 ex_7 + \dot{E}x_{Dest\_Exp} \tag{3.49}$$

Where $\dot{E}x_{Dest\_Exp}$ is the exergy destruction rate of the expansion valve.

3.4.12 System performance

Heat Pump Coefficient of Performance:

$$COP_{Heat\_Pump} = \frac{\dot{m}_5(h_6 - h_5)}{W_9} \tag{3.50}$$

System Energy Efficiency:

$$\eta_{system\ energy} = \frac{w_{35} + \dot{m}_{20}(h_{21} - h_{20}) + \dot{m}_{30}(h_{31} - h_{30}) + \dot{m}_1(h_2 - h_3)}{W_{TOS\_input} - W_{wind\_input}} \tag{3.51}$$

System Exergy Efficiency:

$$\eta_{system\ energy} = \frac{w_{35}+\dot{m}_{20}(ex_{21}-ex_{20})+\dot{m}_{30}(ex_{31}-ex_{30})+\dot{m}_{1}(ex_{2}-ex_{3})}{W_{TOS\_input}-W_{wind\_input}} \qquad (3.52)$$

Where W_{TOS_input} is the power provided by the TOS to the system and W_{wind_input} is the power provided by the wind to the system.

Chapter 4: Results and Discussion

This chapter provides the results and analysis of the proposed energy system for Cambridge Bay, which has been thermodynamically analyzed using the Engineering Equation Solver (EES) and RETScreen ®. The results provided demonstrate the potential of the proposed system over a range of operating parameters. Further, it compares the selected energy system to current systems used in Cambridge Bay for both cost and emissions.

4.1 System Performance

The average lowest temperature in Cambridge Bay is approximately -33°C, however, temperatures can reach extreme lows of -53°C. Therefore the system has been designed to accommodate these extremes, albeit without wind turbine power due to turbine limitations at those temperatures [155]. An initial simulation has been produced with EES at an average low temperature of -32.5°C, see Table A.1. At an ambient temperature of -32.5°C the mass flow rate of water required for heating for housing and farming is approximately 247.5 kg/s and decreases as temperature increases. The hot water supply for the community is fixed at 0.87 kg/s and supplied to the community at 70°C. To supply the heat needed to the water, the ASHP utilizes refrigerant 410a with a mass flow rate of 234.1 kg/s and an inlet temperature of 106.9°C. The power input of the compressor at -32.5°C is calculated based on an energy COP value of 2.0 at 20,807 kW with a calculated exergy COP of 0.6. A pressure of 450 kPa has been used for hot water supply, heating supply and fresh water supply to the community in accordance with industry standards, with pressures being provided by pump #s 6, 7, 8 and 9. Both the hot water supply and fresh water is treated as waste and sent to the liquid waste management at ambient pressure.

Sea water at a constant temperature of 10°C is pumped at ambient pressure and increased to 5,510 kPa to accommodate the operating requirements of the reverse osmosis desalination plant. 40% of the seawater is rejected at ambient pressure through pump # 2, and the remaining 60% is circulated in the system for fresh water. The desalination process operates at approximately 0.0025 kWh/kg processed.

The TOS system produces a constant power output of approximately 110 kW based on the expected solid waste produced by Cambridge Bay and the proposed facility. This system operates with a turbine inlet temperature of 350°C and a steam mass flow rate of 0.397 kg/s. Excess heat is rejected through the condenser at 848 kW, and water is returned to the TOS for circulation.

Community power requirements at state #35 were assumed to be approximately 7534kW, where 20% of power is consumed by housing and 80% by ancillaries such as street lighting, hangar, storage facilities etc. Overall, the energy and exergy efficiencies for the system were found to be 64% and 41%, respectively.

The main sources of exergy destruction rates in this system under the aforementioned operating parameters included the ASHP expansion valve at 7,120 kW, the ASHP heat exchanger at 1882 kW, the condenser at 382 kW, the turbine at 18.5 kW and the evaporator at 2.0 kW, see Table 4.1. The exergy destruction rate in the expansion valve is primarily due to the significant temperature and pressure drops across the valve and should be analyzed further with different parameters or refrigerants to determine if this can be reduced without compromising the rest of the system under the remaining temperature parameters.

Table 4.1: Exergy destruction rates with wind power (kW)

Expansion Valve	Heat Exchanger	Condenser	Turbine	Evaporator
7,120	1,882	382	18.5	2.0

A further requirement of the system design is the energy storage system's capability to provide sufficient power in the absence of wind. Hydrogen storage has been estimated to provide sufficient power to the system for approximately 7 days at the extreme maximum low temperature in the absence of wind and has a replenishment rate of one month at an average wind speed and average minimum temperature. Energy storage requirements have been based on data provided by RETScreen ®.

The following analysis is based on the hydrogen powered system at an average low temperature of -32.5°C with simulation numbers seen in Table A.2. For fuel cell operation, aforementioned assumptions and state points remain the same except states #20 and #30, which are increased due to the heat capture from the fuel cell producing electricity for the system. Heat capture increases the SOFC fuel cell from an efficiency of approximately 60% to 90% producing approximately 18,767 kW of heat to the system. Through this heat, the hot water supply to the community increases from 10°C to 50°C at state #20 and the heating fluid from 30°C to 42.6°C, thus decreasing the power required for the ASHP to 14,263 kW.

The exergy destruction values were similar to the previous simulation in that the expansion valve had the largest destruction of 4,881 kW, followed by the heat exchanger at 867.3 kW, the condenser at 381.9 kW and the evaporator at 1.4 kW, see Table 4.2. For the purposes of this simulation, the TOS system was assumed to be under continuous operation. Overall, the energy and exergy efficiencies for the system were found to be 57% and 38%, respectively.

Table 4.2: Exergy destruction rates with no wind power (kW)

Expansion Valve	Heat Exchanger	Condenser	Turbine	Evaporator
4,881	867	382	18.5	1.4

4.2 Parametric Studies

4.2.1 Power produced

It should be noted that the system has been designed to accommodate extreme minimum temperatures, and this will result in net-positive energy output and, at the same time, exceed hydrogen storage capacity. To accommodate this extra power, the current proposed power plant for Cambridge Bay can take energy being fed back to the local community power plant. Figure 4.1 shows the excess power produced per month based on average monthly temperatures for Cambridge Bay. The excess power produced in the coldest months illustrates the system design accommodating the potential for more extreme weather conditions. Excess power produced is capped at -40°C due to the current operating constraints of wind turbines and the requirement to utilize stored hydrogen for power generation at lower temperatures.

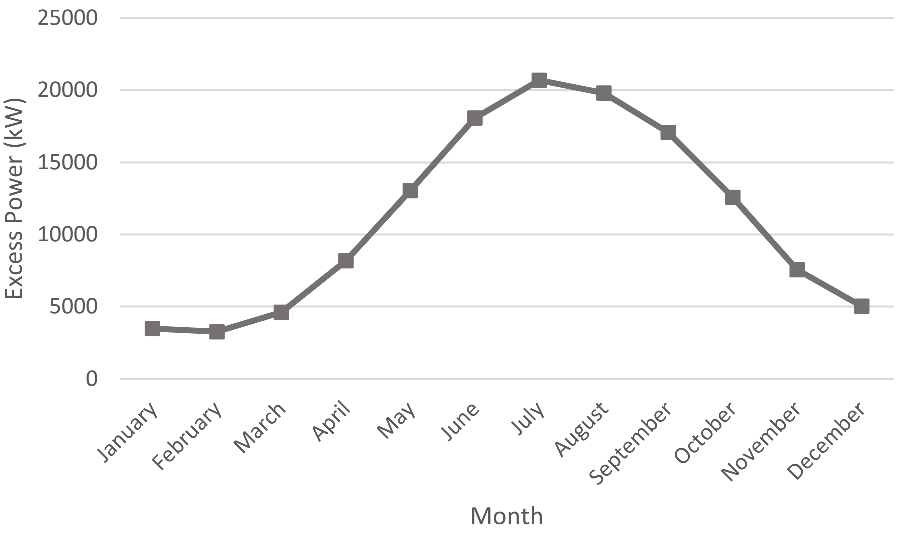

Figure 4.1: Average excess power produced

4.2.2 Community heat load

Another parametric study run was to show the heating load of the community over the course of an average year in Cambridge Bay, see Figure 4.2. Although the heating load is significantly reduced in the months of July and August, it can be seen that there is a constant demand for heat as the highest average temperature is only 9°C. The lowest heating load, correlated with the highest temperature, is in July at 8639 kW. Further, Figure 4.2 shows the direct relationship between the compressor and the heating load of the community, as the heating load decreases, so does the power input requirement for the compressor. The relationship between the compressor and heating load is correlated with the COP of the heat pump, which has been assumed at 2.0 based on improvements in the industry. However, it would be expected that if the COP of the heat pump is 2.0 at extremely low temperatures, the COP would improve as temperature increases, further reducing the power demand from the compressor, as shown below. Figure 4.3 shows the relationship between the power required for the compressor compared to outside temperature, while Figure 4.4 shows the relationship between the heat load compared to ambient temperature.

The temperature in Figure 4.3 illustrates the average temperature experienced in Cambridge Bay per month and is, therefore non-linear as temperature experienced from month to month is non-linear. Through this set of data, it was also found that the heating load requirement for farming was approximately 84% of the overall heating load of the community on any given month.

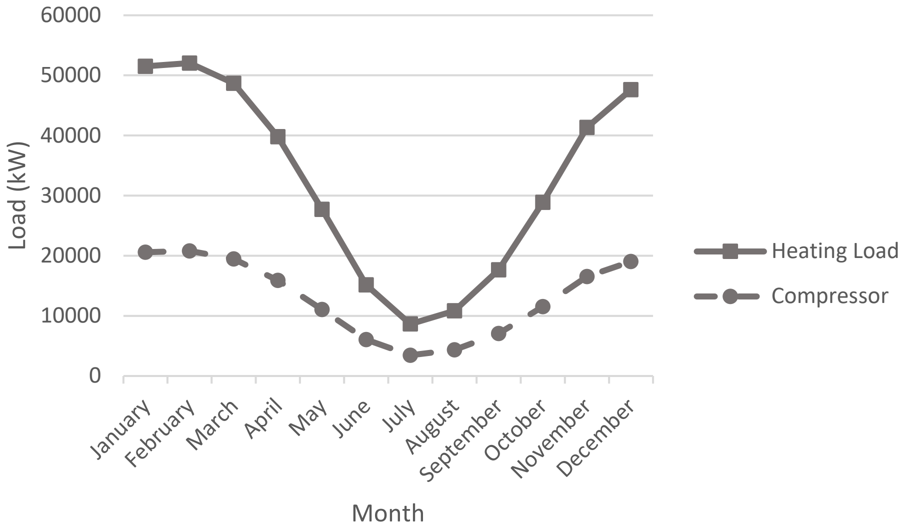

Figure 4.2: Heating load (kW) and compressor power (kW)

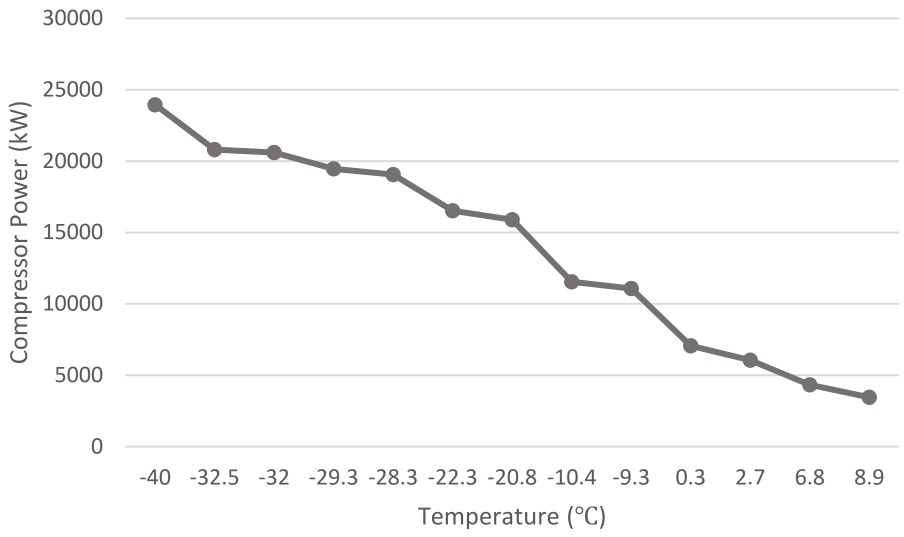

Figure 4.3: Compressor power (kW) vs temperature (℃)

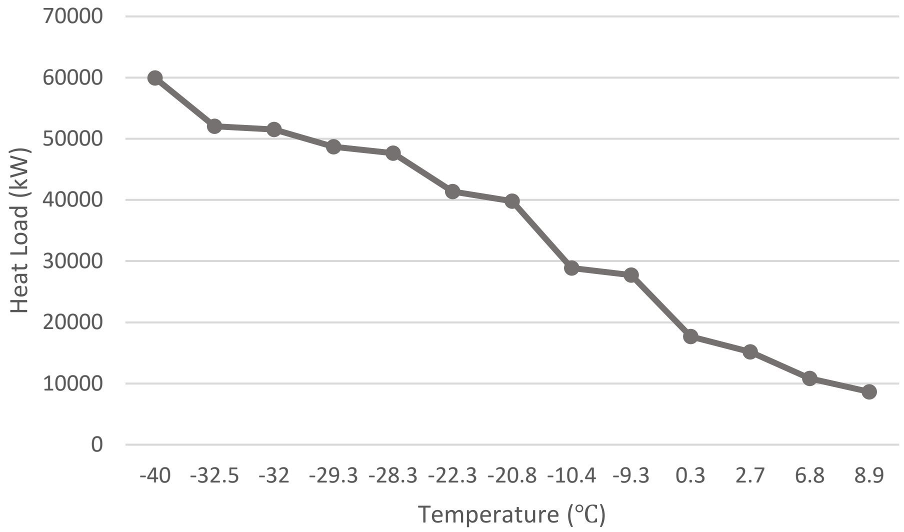

Figure 4.4: Heat load (kW) of community vs temperature (℃)

4.2.3 Heat transfer coefficient

As seen in equation 3.4, dictating the formula for the heat load of the farming buildings in this application, the heat transfer coefficient can heavily influence the overall heat load of the building. Although the preliminary heat transfer coefficient assumed was 0.7 BTU/hr ft^2 ºF, a parametric study was performed utilizing a decreasing heat transfer coefficient to portray the relationship between the overall heating demand of the system, the heat transfer coefficient and the compressor work required. As seen in Figure 4.5, both the heat load and the compressor work have a linear relationship with the heat transfer coefficient – the decrease in the heat transfer coefficient achieves a significant reduction in both heat load and compressor work required for heating.

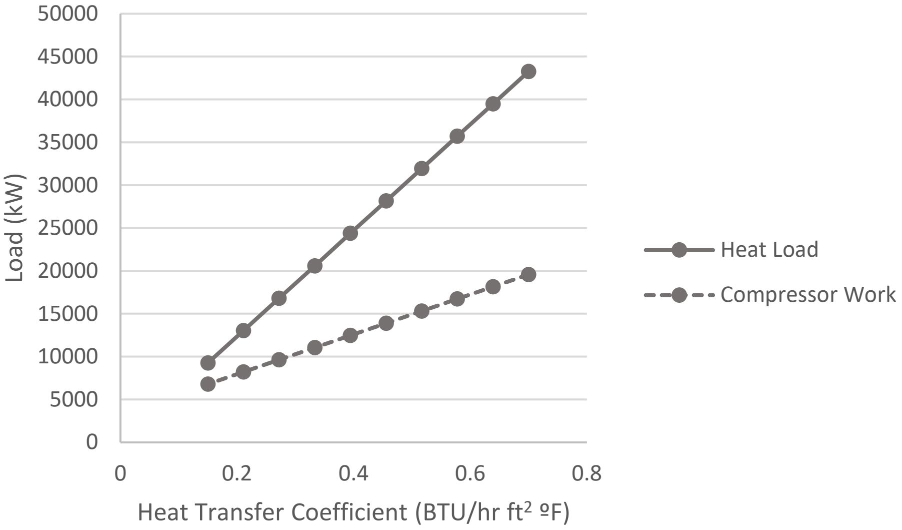

Figure 4.5: Heat load and compressor work vs heat transfer coefficient of greenhouse

4.3 Cost and Emissions Comparison

4.3.1 Cost Comparison

The main source of electricity in Cambridge Bay is an aging diesel power plant currently projected for replacement [156]. Diesel for heating is sold in Cambridge Bay for approximately $1.47/L [157], and electricity for government customers at 87 cents/kWh utilizing the diesel system [158]. Furthermore, under the Nunavut Electricity Subsidy Program, the government subsidizes electricity rates with Cambridge Bay as high as 46 cents/kWh [159].

Construction costs are also a major factor, particularly considering the remoteness of the location and natural constraints such as the permafrost. According to the U.S. Energy Information

Administration, petroleum based generation costs an average of $795/kW in construction costs, whereas wind generation costs an average of $1,498/kW [160]. However, in a recent wind potential analysis in Nunavut, it was found that installation and construction costs could be as high as $4,584/kW with offshore wind up to $6,500/kW in addition to annual maintenance costs [141]. Therefore, it is assumed petroleum based generation plant costs would increase similarly due to the remoteness to approximately $2,432/kW [161].

As discussed, to ensure the system operates seamlessly, it has been designed to accommodate a maximum low of -52°C; however, most extreme climate turbines have an operating envelope maximum of -40°C or higher. Therefore, it is assumed hydrogen conversion would be required for temperatures lower than -40°C. Based on the analysis and parameters provided previously, the power requirements of the community are approximately 46,581 kW. Using costs/kW, total costs for a petroleum based generation plant, onshore wind generation plant, and offshore wind generation plant are $70M, $214M and $302M, respectively. Although petroleum based generation requires less capital for initial operation, operating costs are generally higher and should be compared for a full picture. Furthermore, the reduced costs for petroleum based generation can also be attributed to a lower capacity requirement as energy storage is not required. Factoring in annual maintenance costs of $39/kW, $60/kW and $130/kW for petroleum based generation, onshore wind generation and offshore wind generation with initial startup costs above, it takes approximately five years for onshore wind generation investment to match petroleum based generation and eight years for offshore wind generation to match petroleum based generation investment, see Figure 4.5. Although current technology limits the lifespan of a wind turbine to approximately 20 years and diesel power plants can have a lifespan of 40 years, a re-investment of wind turbines at year 20 using current startup and operating costs also shows the overall cost benefits of wind over petroleum generation, see Figure 4.6.

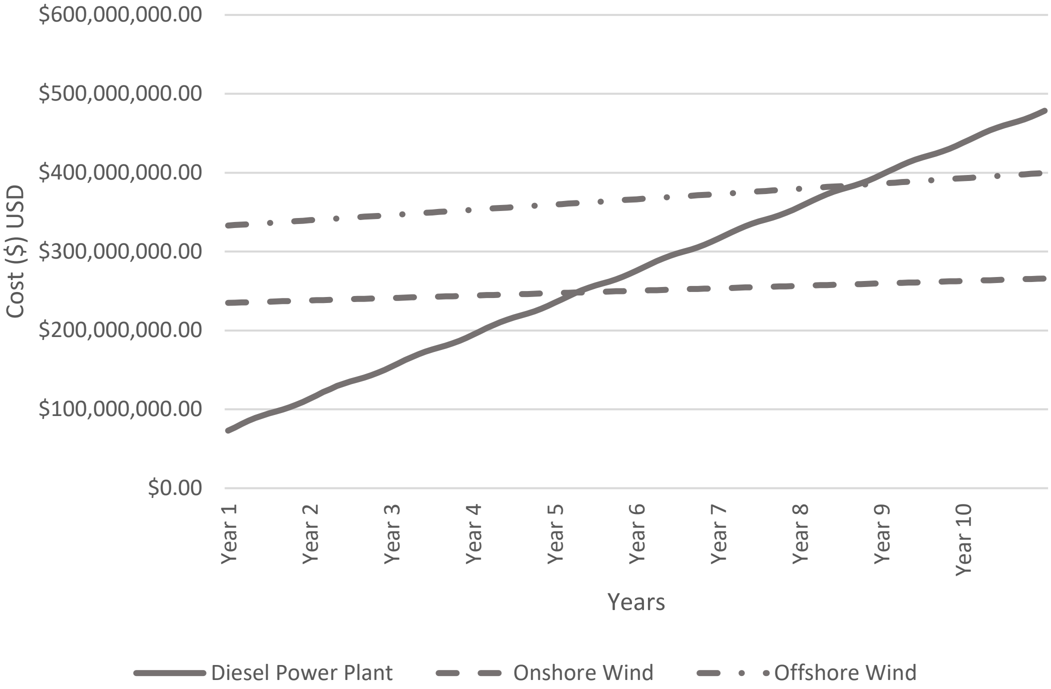

Figure 4.6: Lifecycle cost comparison - diesel vs wind ($)

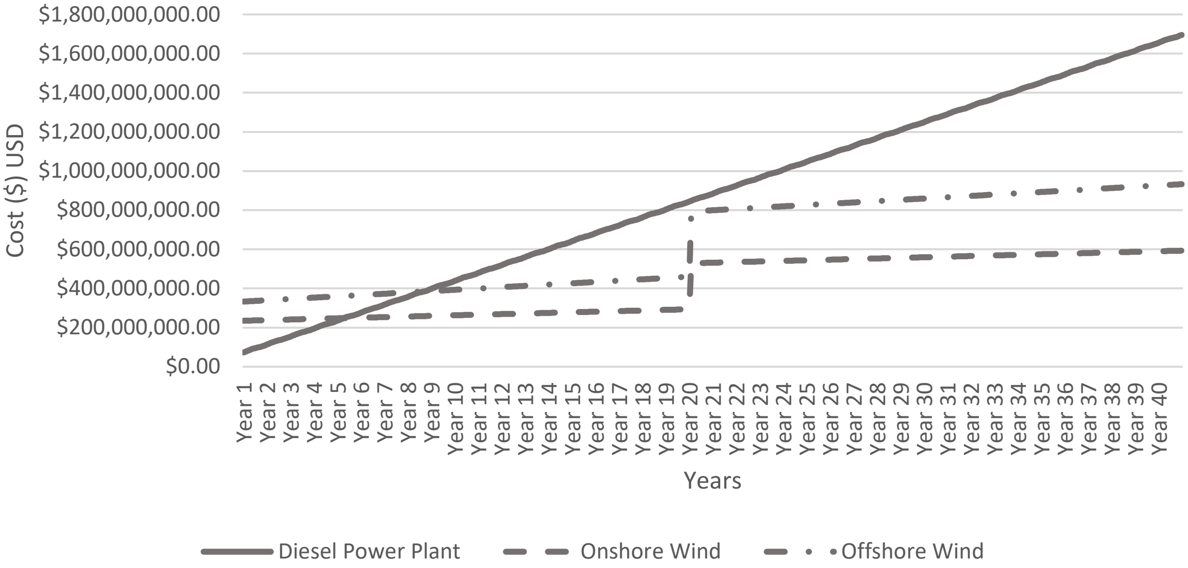

Figure 4.7: 40 year lifecycle cost comparison - diesel vs wind ($)

4.3.2 Emissions comparison

While wind power does not produce direct emissions in the generation of electricity like its diesel counterpart, its lifecycle does. Lifecycle emissions should be factored in when comparing energy systems, including direct, infrastructure, supply chain and maintenance. Due to the remoteness of Cambridge Bay, it is assumed that lifecycle emissions of both diesel and wind electricity generation are at the high end of gCO_2/kWh, resulting in approximately 910 gCO_2/kWh for diesel generation, 56 gCO_2/kWh for onshore wind generation and 35 gCO_2/kWh for offshore wind generation [161]. In a similar comparison to cost, Figure 4.7 illustrates the comparison between diesel, onshore wind and offshore wind power generation over 40 years, showing the benefits of wind generation with respect to CO_2 emissions.

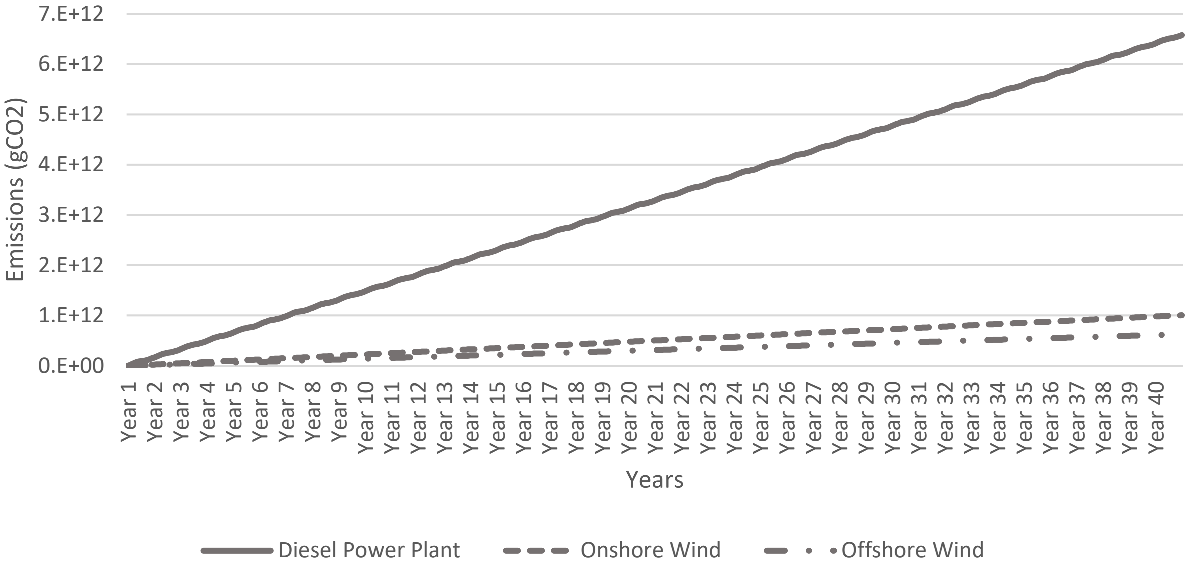

Figure 4.8: Lifecycle emissions comparison diesel vs wind (gCO2)

Chapter 5: Conclusions and Recommendations

5.1 Conclusion

The proposed location for this study is Cambridge Bay, Nunavut, due to its central location in Canada's Arctic as well as its current airport infrastructure, community population and shipping route location. After a review of potential energy systems for this location and the parameters of the military base, a single system was developed for a community of 1,000 people.

The proposed system is a self-contained energy system in the Arctic utilizing wind and heat from waste incineration that provides sustainable energy to meet the aforementioned criteria, with excess electricity given back to the power plant in Cambridge Bay for the community. Employing EES software and RETScreen ®, the analysis and parametric studies showed the proposed system has the potential to provide sufficient heating, electricity and fresh water to the community throughout the year utilizing wind as its primary source of energy. Moreover, when factoring in the stochastic nature of wind and the operating limitations of current wind turbine technology, excess energy is stored chemically in the form of hydrogen, which is able to support the community during extremely low temperatures in the absence of sufficient wind power for seven days. The total system energy efficiency was found to be 64%, and the exergetic efficiency was 41%. System capacity was calculated at 51 MW with a hydrogen storage capacity requirement of 229 tons. Total fresh water capacity was calculated at 6.4 kg/s with 0.9 kg/s for hot water, 4.1 kg/s for fresh water and 1.4 kg/s for farming.

The analysis also showed the wind powered system had a cost breakeven point between five to eight years and produced less than 9% lifecycle emissions in comparison to its diesel counterpart. Finally, excess electricity of up to 97 gWh produced by the system yearly has the ability to benefit the community of Cambridge Bay through feedback into the local power plant.

Overall, the objectives of this thesis have been achieved, albeit with some challenges surrounding the ASHP. Although overcome through utilizing R410a, one such challenge included the selection of a refrigerant which would provide the characteristics required to achieve the thermal transfer necessary to provide heating and hot water to the community.

5.2 Recommendations

Although this thesis forms the basis for a potential energy system to support a military base in the Arctic, there are a number of other studies and work that could be conducted to build on this work. Listed below is a non-exhaustive list of potential future work:

- Further investigation and improvements in the proposed ASHP, including an overall reduction in exergy destruction and a review of efficiencies utilizing a varying range of COPs dependent upon ambient temperatures.

- A detailed analysis of the overall cost of the system, including full lifecycle costs and a comparison of other potential systems.

- An analysis of utilizing the TOS condenser waste heat to preheat refrigerant in the ASHP prior to entering the compressor.

- A cost/benefit analysis on farming in the Arctic is taking into account the significant heating demand.

- Comparison of farming methods in the Arctic to improve overall system effectiveness.

- A geological survey to determine the suitability of onshore wind in the proposed location vs offshore wind considering cost and permafrost limitations.

- A socio-economic review of the proposed system, including the impact due to the proximity to the community, land utilized and employment potential.
- An environmental impact review including impact on wildlife and habitats, impact on water, air, ground and permafrost.

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Appendix

Table A.1: Thermodynamic analysis state points at -32.5°C utilizing wind power

State	Specific Entropy (kJ/kg-K)	Temperature (°C)	Specific Exergy (kJ/kg)	Specific Enthalpy (kJ/kg)	Mass Flow Rate (kg/s)	Pressure (kPa)
0	6.643	-32.5		240.5		101.3
1	6.669	350.1	2859	3106	0.397	3447
2	6.862	193.1	2537	2830	0.397	690
3	1.986	164.4	1575	694.5	0.397	690
4	1.986	164.8	1578	697.5	0.397	3447
5	1.881	106.9	1398	492.3	234.1	4033
6	1.364	62.3	1344	314.6	234.1	4033
7	1.49	-32.6	1314	314.6	234.1	242.7
8	1.881	-32.5	1314	408.7	234.1	242.7
10	0.1511	10.1	1364	42.12	10.64	101.3
11	0.1511	10.1	1369	47.53	10.64	5515
12	0.1511	10.1	1364	42.12	4.256	101.3
13	0.1511	10.1	1364	42.12	4.256	101.3
14	0.1511	10.1	1364	42.12	6.385	101.3
15	0.1511	10.1	1364	42.12	6.385	101.3
16	0.1511	10.1	1364	42.12	6.385	101.3
17	0.1511	10.1	1364	42.47	6.385	450
18	0.1511	10.1	1364	42.12	0.87	101.3
19	0.1511	10.1	1364	42.12	0.87	101.3
20	0.1511	10.1	1364	42.12	0.87	101.3
21	0.9551	70.1	1421	293.1	0.87	101.3
22	0.9551	70.1	1421	293.1	0.87	101.3
23	0.9551	70.1	1422	293.5	0.87	450
24	0.4367	30.1	1379	125.8	7.255	101.3
25	0.4367	30.1	1379	126.2	7.255	450
26	0.4367	30.1	1379	125.8	6.53	101.3
27	0.4367	30.0	1379	125.8	6.53	101.3
28	0.4367	30.1	1379	125.8	247.5	101.3
29	0.4367	30.1	1379	126.2	247.5	450
30	0.4367	30.1	1379	126.2	247.5	450
31	0.9549	70.1	1422	293.4	247.5	450

Table A.2: Thermodynamic analysis state points at -32.5°C utilizing hydrogen power

State	Specific Entropy (kJ/kg-K)	Temperature (°C)	Specific Exergy (kJ/kg)	Specific Enthalpy (kJ/kg)	Mass Flow Rate (kg/s)	Pressure (kPa)
0	6.643	-32.5		240.5		101.3
1	6.669	350.1	2859	3106	0.397	3447
2	6.862	193.1	2537	2830	0.397	690
3	1.986	164.4	1575	694.5	0.397	690
4	1.986	164.8	1578	697.5	0.397	3447
5	1.881	106.9	1398	492.3	234.1	4033
6	1.364	62.3	1344	314.6	234.1	4033
7	1.49	-32.6	1314	314.6	234.1	242.7
8	1.881	-32.5	1314	408.7	234.1	242.7
10	0.1511	10.1	1364	42.12	10.64	101.3
11	0.1511	10.1	1369	47.53	10.64	5515
12	0.1511	10.1	1364	42.12	4.256	101.3
13	0.1511	10.1	1364	42.12	4.256	101.3
14	0.1511	10.1	1364	42.12	6.385	101.3
15	0.1511	10.1	1364	42.12	6.385	101.3
16	0.1511	10.1	1364	42.12	6.385	101.3
17	0.1511	10.1	1364	42.47	6.385	450
18	0.1511	10.1	1364	42.12	0.87	101.3
19	0.1511	10.1	1364	42.12	0.87	101.3
20	0.1511	10.1	1364	42.12	0.87	101.3
21	0.9551	70.1	1421	293.1	0.87	101.3
22	0.9551	70.1	1421	293.1	0.87	101.3
23	0.9551	70.1	1422	293.5	0.87	450
24	0.4367	30.1	1379	125.8	7.255	101.3
25	0.4367	30.1	1379	126.2	7.255	450
26	0.4367	30.1	1379	125.8	6.53	101.3
27	0.4367	30.0	1379	125.8	6.53	101.3
28	0.4367	30.1	1379	125.8	247.5	101.3
29	0.4367	30.1	1379	126.2	247.5	450
30	0.4367	30.1	1379	126.2	247.5	450
31	0.9549	70.1	1422	293.4	247.5	450