10-16-2019

Feasibility Study of Sustainable Energy Alternatives to Power Remote Communities in Northern Ontario

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Recommended Citation
Nijhawan, Mudit, "Feasibility Study of Sustainable Energy Alternatives to Power Remote Communities in Northern Ontario" (2019). *Electronic Theses and Dissertations*. 8147.
https://scholar.uwindsor.ca/etd/8147

Feasibility Study of Sustainable Energy Alternatives to Power Remote Communities in Northern Ontario

By

Mudit Nijhawan

A Thesis
Submitted to the Faculty of Graduate Studies
through the Department of Mechanical, Automotive, and Materials Engineering
in Partial Fulfillment of the Requirements for
the Degree of Master of Applied Sciences
at the University of Windsor

Windsor, Ontario, Canada

2019

Feasibility Study of Sustainable Energy Alternatives to Power Remote Communities in Northern Ontario

by

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DECLARATION OF CO-AUTHORSHIP/ PREVIOUS PUBLICATION

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I hereby declare that this thesis incorporates material that is result of joint research, as follows:

Chapter 4 of the thesis was authored by Mudit Nijhawan under the supervisions of Professor Ofelia A. Jianu. In all cases, the key ideas, primary contributions, experimental designs, data analysis, interpretation, and writing were performed by the author, and the contribution of the co-author was primarily through the feedback on refinement of ideas and editing of the manuscript.

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ABSTRACT

Remote communities in the North of Ontario survive in isolation as their distance to the southern industrial and electrical sector of the province limits their accessibility to the major southern grid. The lack of grid connection has led to antiquated methods of power generation, which pollute the environment and deplete the planet of its natural resources. One solution to these problems is the storage of electricity as hydrogen gas through electrolysis. This work determined the feasibility of introducing clean energy alternatives and provided a fuel blend option consisting of solar, wind, and hydrogen energy sources. To determine a fuel blend for Northern communities, an exergy analysis and an analysis of emissions of CO_2 from the production of raw feed material in the construction of the energy systems is performed. When comparing the hydrogen fuel cell alone, exergy efficiency and emissions were more preferable than wind and solar. Although, when electrolysis and transportation emissions of the fuel cell were considered, the fuel cell became a less preferable alternative. The implementation of a fuel cell energy source would require the construction of a hydrogen generation infrastructure to allow for hydrogen production from the southern grid system and provide flexibility to the grid.

ACKNOWLEDGEMENTS

First and foremost, I want to acknowledge my mentor and supervisor Dr. O. A. Jianu for her continued support throughout my graduate and undergraduate studies. I never expected when I began working for her during my undergraduate term that I would ever continue my education after graduation and go on to do a post graduate degree. I want to thank her for fanning the flames of my curiosity and pushing me to always do better and to always be better. I do not think I could have ever found a better mentor.

I want to thank my committee members Dr. E. Tam and Dr. J. Defoe for their valuable guidance and input throughout my research. I also want to thank the rest of the Sustainable Energy Research Group for their input and assistance during our weekly meetings.

I am also grateful to my family, for without their support none of this would be possible. Words cannot express the gratitude I have towards my mother, as without her hard work in raising me, I would not be where I am today. I also want to thank my father for always pushing me and to always accept any challenge that is ahead of me.

I also want to thank I also want to thank my friends Carson, Kelvin, Mohamad, Natasha, Nicholas, and Talveen for their humor and encouragement.

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LIST OF ABBREVIATIONS/SYMBOLS

BOP	Balance of Plant
CAD	Canadian Dollar
CdTe	Cadmium Telluride
CdS	Cadmium Sulfide
CO_2	Carbon Dioxide
CIFS	Copper Indium Gallium Selenide
CFC	Chlorofluorocarbons
GHG	Green House Gases
DOE	Department of Energy
GaSA	Gallium Arsenide
GWP	Global Warming Potential
HORCI	Hydro One Remote Communities Initiative
IESO	Independent Electricity System Operator
MEA	Membrane Electrode Assembly
NOCT	Nominal Operating Cell Temperature
PEM	Polymer Electrode Membrane
PEMFC	Polymer Electrode Membrane Fuel Cell
PVC	Polyvinyl Chloride
PVGIS	Photovoltaic Geographical Information System
RE	Renewable Energy
RETScreen	Renewable Energy Technology Screen
SI	International System of Units

NOMENCLATURE

A	Area
β	Temperature Coefficient
C	Celsius
C_p	Specific Heat Capacity
ex	Specific Exergy
$\dot{E}x$	Exergy
F	Fahrenheit
p	Pressure
R	Gas Constant
S_t	Solar Irradiance
T	Temperature
ρ	Density
ω	Humidity Ratio
ψ	Exergy Efficiency
η	Cell Efficiency
ν	Water Vapor

Subscripts

Cell	Solar Cell
Chem	Chemical
des	Destruction
kin	Kinetic
Phy	Physical
Ref	Reference
t	Total

Chapter 1 – Introduction

1.1. Motivation

One of the greatest perils being faced by humanity today is the threat of climate change which is being caused by the consumption of fossil fuel [1]. Established methods of power generation through the consumption of fossil fuels are unsustainable and have led to the release and accumulation of greenhouse gases in the atmosphere, which may be the leading cause of an increase in global temperature [2]. Additionally, conventional energy systems require extraction of the planet's natural resources which results in further damage to the environment. There are over 292 remote communities within Canada with many of them using diesel generators as the primary means of electricity generation. Many communities are currently facing load restriction resulting in communities halting infrastructure expansion [3]. The combination of greenhouse gas emissions and limitations on communities provides a chance for the implementation of renewable energy sources (i.e. wind, solar, hydrogen), however the application of such technologies requires the assessment of resources at the community. Assessing of such resources is being performed through an exergy analysis, to quantify the quality of the resources at the community. This analysis can assist in choosing an energy generation blend based on two objectives: the minimization of greenhouse gas emissions from the raw feedstock materials in the production of renewable energy technologies and the maximization of resource utilization. Cost analysis and land use, although important for the consideration of an energy blend are not considered for the purpose of this research. The research instead focuses only on determining the feasibility through exergy efficiency analysis and GHG emissions emitted from the raw materials.

The major electricity grid of Ontario, which is located in southern Ontario and provides electricity to the majority of residents and businesses, generates electricity while producing very little greenhouse gas emissions. This is due to the diverse mix of clean power generation technologies such as wind, solar, hydro, and nuclear. Due to intermittent nature of wind and solar energy and the changing demand of electricity, wind and solar technologies are often curtailed and excess energy is often sold to neighbouring grids at a loss.

The lack of electricity storage is partially to blame for these problems. One solution to these problems is the storage of electricity as hydrogen gas through electrolysis. This technology can provide flexibility to the grid and can be used to transport power to remote communities, where hydrogen can be used through a fuel cell to provide electricity and possibly heat. The use of hydrogen can also offset the millions of tons of GHG emissions from the communities during power generation and diesel transportation. The generation of hydrogen from excess power is explored in chapter 2, section 2.1.2. Wind and solar energy technology feasibility is also explored for the communities, as the current hydrogen generation infrastructure is currently nonexistent.

1.2. Background

Conversion and utilization of energy via fossil fuel combustion are leading to unsustainable habits, such as electricity generation, that may damage the environment by continuing the output of greenhouse gasses (GHG), deplete the ozone layer and pollute the planet's water supply. To prevent further damage, the use of renewable energy methods is needed and the demand for such methods is on the rise [4]. Climate change is being brought out by the rise in global temperature. Increasing global temperatures lead to an increase in sea level. The "knock on" effect caused by the emission of carbon dioxide (CO_2) is prevalent as the changing temperature and rising sea levels disrupts natural ocean currents contributing to extreme weather events [5].

Solar energy is the major component driving the weather conditions on the planet, it is a composition of light of different wavelengths, out of which 99% occurs in short wave lengths (0.15 to 4.0 μm). Of the 99%, 9% is in the ultraviolet spectrum, 45% in the visible spectrum, and 46% in the near infrared spectrum. Roughly 70% of the solar radiation is absorbed by the earth and the atmosphere, 3% is absorbed by the stratosphere, 16% by the troposphere, and the remaining 51% is absorbed by the Earth's surface. Figure 1 shows the incoming energy heats the Earth's atmosphere providing the energy necessary for life. In order for the Earth to maintain an energy balance the incoming 70% of the energy is reflected in the form of long wave radiation (4 – 100 μm) in infrared and thermal spectrums [6]. The long wave radiation is subsequently trapped by CO_2, water vapor, and other chlorofluorocarbons (CFC) and thus contribute to the warming of the atmosphere.

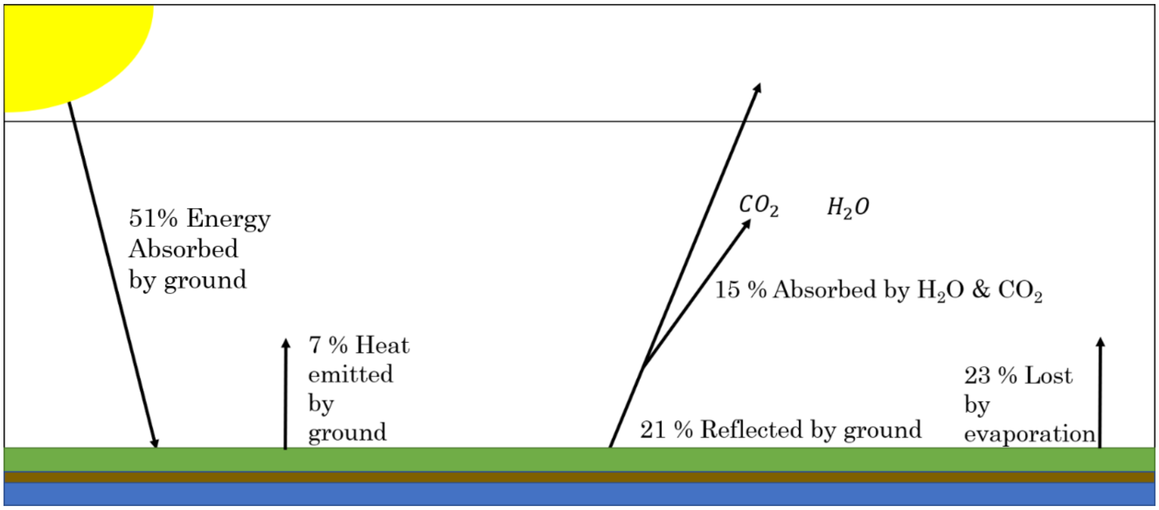


Figure 1 Simplified Greenhouse Effect in Earth's Atmosphere [2]

The concentrations of these components proportionally impact the amount of energy tapped within the atmosphere and thus, a high concentration of either will result in a greater degree of warming. The creation of this "insulating" gas around the Earth by CO_2 is similar to the operation of a greenhouse, hence the term the Greenhouse effect. This effect implies rising global temperatures which result in the melting of glacial ice contributing to increasing sea level and subsequently climate change. Climate change brings with it a whole host of problems such as extreme weather events [5], food shortages [7], and consequently economic instability. To tackle the threat of climate change, focus should be placed upon decreasing the emission of greenhouse gases. GHGs are emitted due to the result of various processes by the industrial sector (see Figure 2), with the primary source being the conversion of fossil fuels to power

[8]. Thus, the strides towards a solution should focus on changing the means of energy conversion methods.

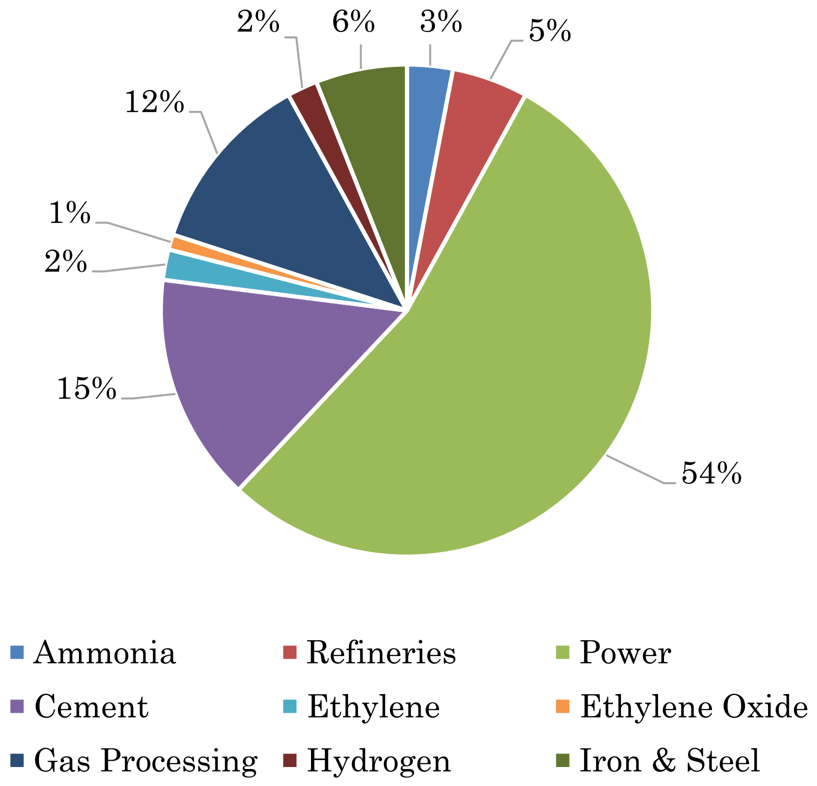


Figure 2 Greenhouse Gas Emissions from Industrial Process

Data from the Environmental Protection Agency (EPA) also showed that the electricity and industry processes combined generate a total of 46% of total emissions, agriculture and land use result in 24% of global emissions, and transportation results in 14% of total emissions [9]. One such solution is the mass adoption of clean energy methods to meet the ever-growing energy demands of the world as they utilize renewable fuels, fuels that do not emit CO_2 during their consumption, to generate electricity without the emission of greenhouse gases, and thus, do not contribute to climate change. To tackle the problem of climate change, there has been an implementation of climate focused policy throughout the world and the government of Canada has implemented the *Pan – Canadian Framework on Clean Growth and Climate Change* [10], which aims to grow the clean energy economy and to reduce GHG emissions. Focusing on electricity production, the government has outlined four major objects: Increase renewable and non-emitting energy sources; connect clean power to places that need it (i.e. remote communities); modernize electrical systems; and reduce the reliance on diesel while working with indigenous people and northern and remote communities [11]. The focus on remote communities is prevalent due to their use of antiquated means of energy generation and their growing populations. Remote communities are defined by a lack of electrical connection from the larger electricity grid system. Currently, there are upwards of 292 remote communities within Canada [12, 10] and roughly 30 communities within Ontario (see Figure 3) with a combined population of 15,000 people. Their remoteness results in various social, technical, and economical challenges. One of the many challenges being faced by the communities is energy production, these communities obtain their power from diesel generators [14]. Out of the 292 communities around 140 of them used diesel generators and consumed more than 465 million liters of diesel and contributed to 1.2 million tons of CO_2 (700 million tons of CO_2 emitted by all of Canada, 2016) [10, 12]. Some of the communities have a singular grid while some are interconnected by a larger grid system. While there are projects in place to convert the individual grids to a larger centralized grid, very little has been done to move these communities to a renewable energy source.

The reliance on diesel creates a variety of issues ranging from environmental to financial problems. The primary concern is that the burning of fossil fuels produces CO_2 which, as mentioned, is a greenhouse gas. Figure 3 provides the fossil fuel consumption of Ontario's communities and indicates that the combined consumption of fuel per year is more than 26 million liters of fuel (69 thousand tons of CO_2). An issue that arises from the reliance on fossil fuels is the need for fuel transportation, which is typically transported to the communities via truck or by airplane. Transportation creates numerous concerns such as the potential of spills during transport accidents, it is also limited by seasonal events and thus it can be very intermittent. Using vehicles further leads to greenhouse gas emissions, close to 13 thousand tons of CO_2 as measured in 2015 [16] by communities in Ontario. Fuel as a market commodity is constantly fluctuating in price and over time will increase in price, thus the price of electricity paid by the communities will also increase and due to the expensive nature of the fuel the price of energy generated can be ten times higher than the primary grid [16].

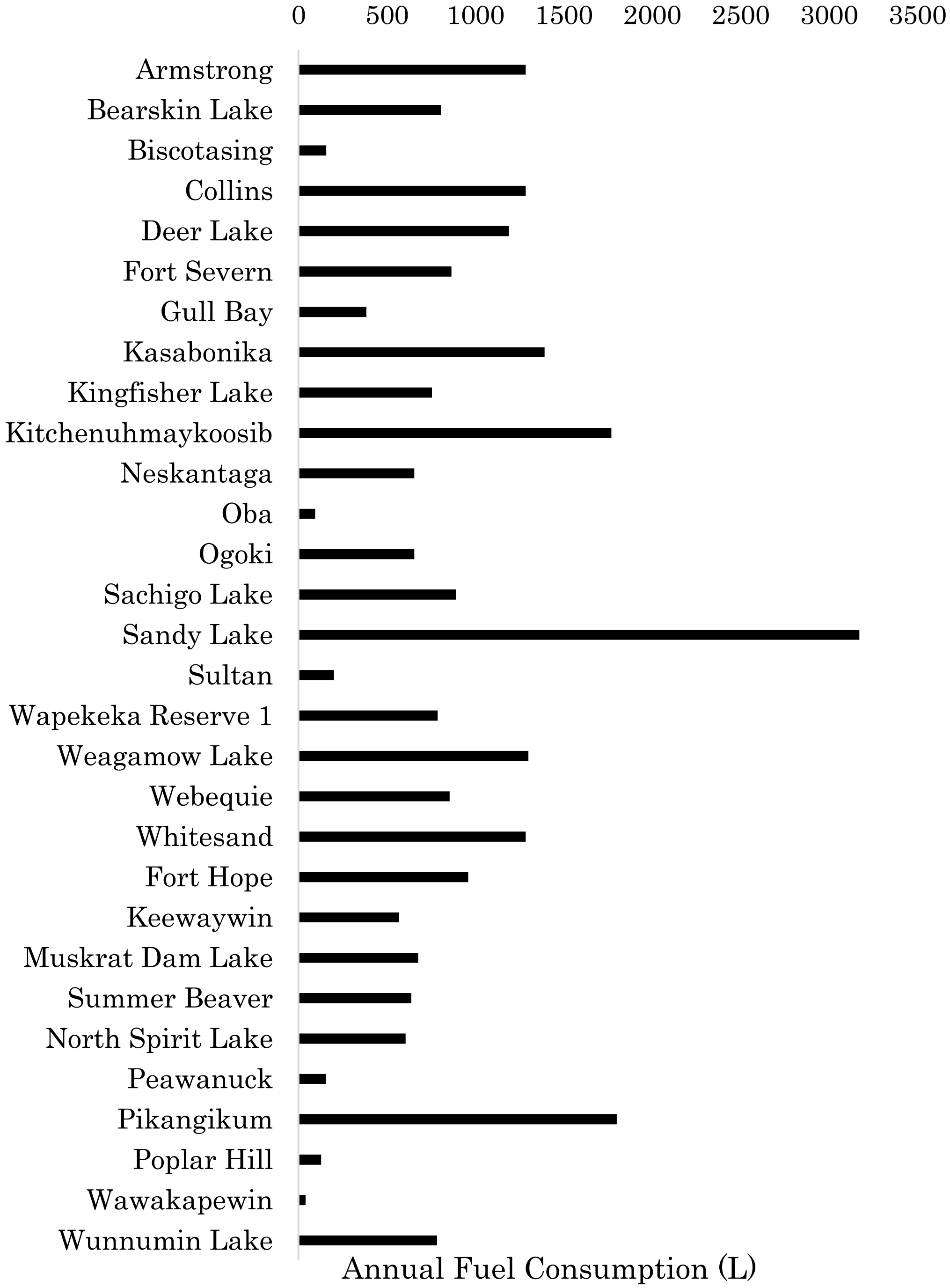


Figure 3 Ontario Remote Communities Diesel Consumption (2016)

1.3. Sandy Lake Community

The research focuses on the largest community by population in Ontario, which is the community of Sandy Lake. The community is a fly in community and during the winter months is accessible by the winter road network. Hence, the approximately 2000 members of the community benefit from this road system between January to March. The community, which has a land area of approximately 44 square kilometers, is located in North–Western Ontario and is home to the Sandy Lake Indian Reserve. As seen in Figure 3 it is the community with the highest fuel consumption, consuming more than 2.7 million kg of diesel in 2016. Fuel is delivered to the community by two pathways, trucks and by air and resulted in the emission of 2700 tons of CO_2)

1.3.1. Community Grid History & Requirements

The energy blend for the community should provide energy for the remote community during a 20-year period, as such the community's energy demands were determined. A report by the Hydro One Remote Community Initiative which was produced in the year 2017, shows that the community is supplied by 4 diesel generators [17], see Figure 4. The community's current demand had reached up to 85% of the total rated generator site capacity of 3050 kW. This data is useful as it provides the communities current growth, which can be used to forecast the future demand of energy, thus providing the size of the community's power plant for future use. Of course, there are many variables that can affect the community's current and future growth, for example, assessments at the location of Sandy Lake have shown a possible deposits of gold underground, should mining and exploration begin an influx and sudden growth of community inhabitants could surpass the model's projections and thus render it obsolete. As explained before Sandy Lake's current load is more than 85% of their power supply, communities begin facing a load restriction when the supply has reach 75% preventing their infrastructure growth. This is an important incentive to supplement the existing facilities with a renewable source of energy.

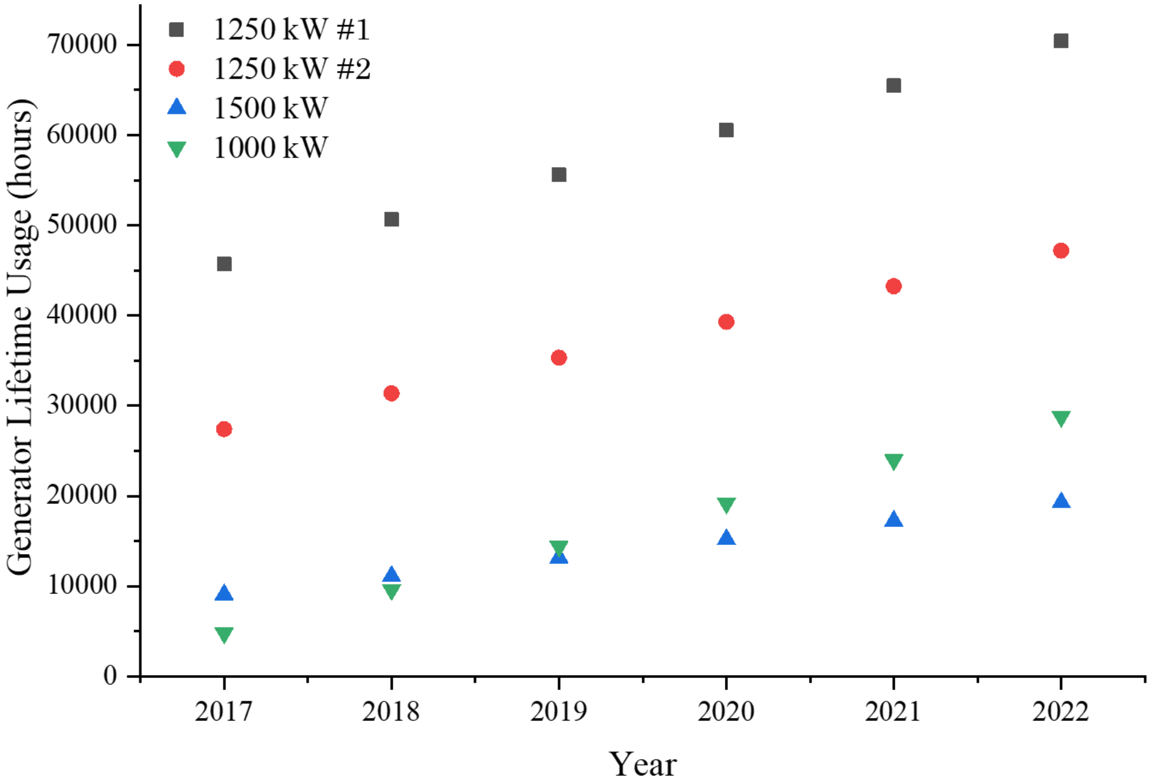


Figure 4 Sandy Lake Cumulated Generator Usage

The results of the analysis can be used with future projections of the community demand to develop an energy blend. The implementation of a clean energy blend to provide 100% of the community's energy needs would also offset the greenhouse gas emissions from the annual consumption of 3.2 million liters of diesel, based on current consumption, and further reduce the emission from transportation (12 thousand tons CO_2 combined in 2015).

1.4. Objectives and Scope

This thesis aims to provide a method to develop a clean energy blend for remote communities. Determining an energy carrier blend depends on two major analysis methods: the analysis of the natural resources available to the communities by an exergy analysis and the production of carbon dioxide from the raw feedstock material used in the production of the energy blend. Exergy is defined as the maximum usable energy that can be obtained from a system; thus, it can be used to determine the quality of a resource. Unlike energy, exergy *can* be destroyed, meaning that once a system has done work, its remnants cannot be used to perform work of a similar or greater magnitude. The exergy analysis is performed by analyzing the various thermodynamic properties of the resources before and after they have been used to generate the rated electricity. The analysis will explore the usability of the resources and provide an efficiency value for each of the three energy production methods. Working on the concept of efficiency the energy production methods are explored through a greenhouse gas emissions analysis, which quantifies the impact each of the energy methods have on the environment. A greenhouse gas emissions analysis of the raw feedstock materials of the three energy generation methods is performed. The results of the analyses are used to develop an ideal energy blend for the community. Cost was not explored for the purpose of this study due to the diverse range of vendors and products available to the market. Cost would also greatly be impacted by the selection of the power generation site, for example the construction of a wind farm or solar farm would need to be considered and impact of construction would need to be explored. Site selection on its own would require a major analysis and the need to travel to the community to consider geological conditions was not possible.

1.5. Outline of Thesis

This thesis has first and foremost explored the community at hand hence, the community's energy demand was assessed, and the future energy requirements was determined. All the community assessment was performed through a literature review (Chapter 2) and through historical data, which was obtained through Environment Canada. The procedure (Chapter 3) explains the various process for the exergy and GHG emissions analysis. Natural resources available to the community were assessed and the quality of the resources was presented. Local weather data was obtained from the Government of Canada's weather data repository and was used to determine the quality of solar and wind resources available to the community. Generator supply and grid demand data for the southern grid system was obtained from the Independent Electricity System Operator, and the resulting hydrogen production was calculated from the excess grid electricity. A life cycle assessment was performed to determine the quantity of CO_2 that would be emitted during the production of the three energy methods and that was compared to the operation of the diesel generator, to determine the energy blend with the lowest emitted GHG. The results of the exergy analysis and GHG emissions assessment, during the various times of the year, are provided in the results section (Chapter 4). Finally, the information gathered from the exergy analysis and the life cycle assessment provided the energy blend that can be used by the community, this information is provided in the results and discussion section (Chapter 5). A substantial assessment of the community and its surroundings would be required prior to construction of the proposed energy blend, as such, a future works section (Chapter 6) is also provided.

Chapter 2 – Literature Review

2.1. Current Power Generation Methods

Canada is home to more than 292 remote communities with a majority of them receiving their electricity from diesel generators. Figure 5 shows the energy sources for the remote communities within Canada: the vast majority of electricity is generated through the use of diesel fuel.

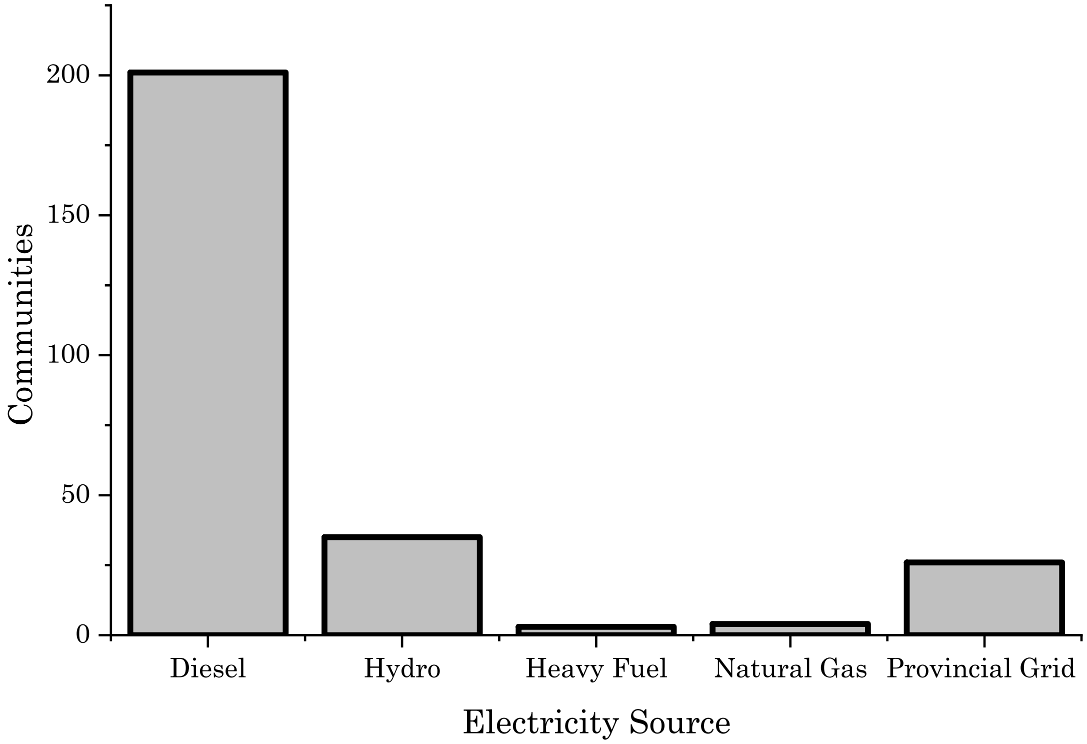


Figure 5 Remote Communities Energy Sources [18]

Delivery of fuel to these remote communities is challenging as it can result in accidents [19] and is concerning as it contributes to greenhouse gas emissions. It is supplied by two generators each at an output of 1250 kilowatt (kW), one generator at 1500 kW, and one generator at 1000 kW diesel generators (Figure 6 for reference) and a combined station output of 3050 kW. The community has yearly peak loads of 2370 to 2570 kW between the years 2013 and 2016, throughout the years with HORCI forecasting the community load exceeding the 75%, of supply leading to load restriction [17] and has resulted in a halt on infrastructure growth and has caused economic stagnation of the community. According to HORCI reports, growth in demand is expected in the community [17], as such the designed peak demand should be used to size up the community energy blend. To reduce the likelihood of other communities facing load restrictions, utilities and the government of Canada are upgrading community infrastructure by adding addition diesel power supply. This solution creates further problems by increasing the demand for fuel and increasing the emissions of GHGs. It may be beneficial to utilize renewable energy systems to supplement the increasing demand for energy, rather than a renewal of diesel generations. These renewables would work with the existing infrastructure which can offer a reliable back up while renewables would be used as the primary source of energy generation. The southern grid is the electrical grid which services the Greater Toronto Area and the surrounding area near the great lakes, see Figure 6, the small dashed, larger dashed, and solid black lines represent the 115 kV, 230 kV, and 500 kV power lines respectively.

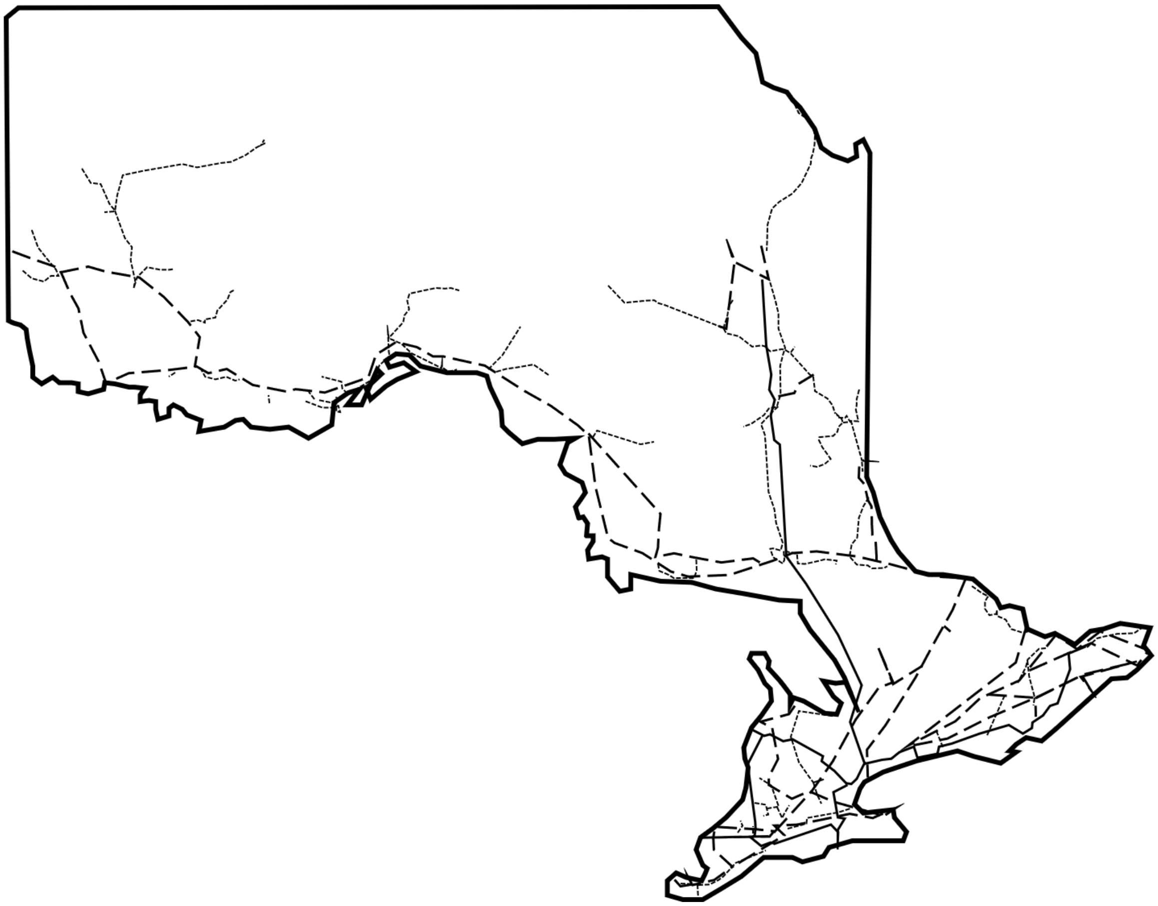


Figure 6 Ontario Southern Grid Transmissions System (reproduced from IESO [20])

2.2. Grid curtailment

One of the primary concerns of the grid balance is the lack of grid flexibility (storage). Ontario produces the vast majority of its energy through nuclear power, which is provided by three power stations: Bruce power, Pickering Power plant, and Darlington power plant and provide a total of 13500 MW of energy to the province [21]. Power is also provided by 66 hydroelectric dams with a combined capacity of 8872 MW of energy, followed by wind with 4826 MW, solar power with a capacity of 2291 MW, and approximately 400 MW produced by natural gas, biomass and petroleum products. Due to the diverse supply of energy to the southern grid, the control of the grid is quite complex and without the flexibility of energy storage, often leads to unfavorable energy transmission decisions. Supply typically being greater in the province of Ontario is often greater than demand as seen in Figure 7 and due to a lack of storage, energy is often sold at a loss. Hence, this study explores the feasibility of hydrogen as an energy storage alternative of the excess and curtailed power within the Southern grid.

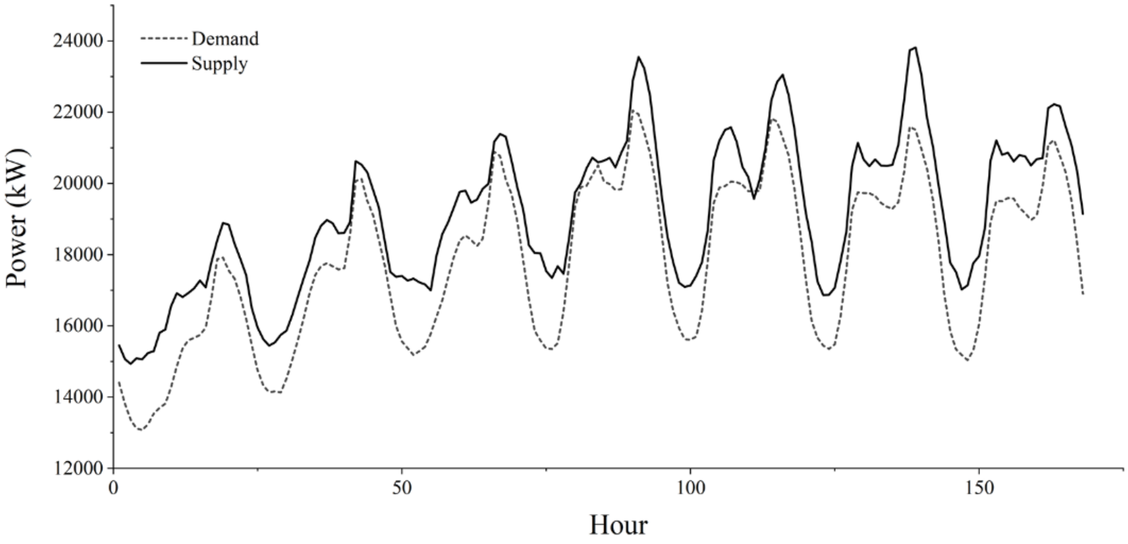


Figure 7 Supply and Demand Curve for Ontario 2010 [22]

Figure 7 displays the energy supply and demand of the province of Ontario during the first week of 2010. The dashed line represents the provinces demand and the black line represents the provinces power supply. The difference in demand and supply is corrected by the IESO by being sold to other customers (United States, Quebec, and Manitoba) [23]. The use of energy storage would allow for greater flexibility as excess energy during grid maneuvers could be stored [24]. The addition of a variable load, which can allow for the storage of energy is beneficial as it would allow for greater grid flexibility and, more importantly, allow for the production of extra energy for times when the supply is less than the demand [24, 25] . There have been many proposed methods of energy storage [27] ranging from underwater compressed air storage [28], flywheel energy storage [29], pumped water storage [30], and finally energy storage through batteries and capacitors [31]. The primary idea behind all the energy storage methods is to store off-peak energy and to supply it back to the grid during peak times. The thesis explores the use of electrolysis to convert electricity to hydrogen and oxygen which can then be stored and later reused through a fuel cell to supply power to the remote community's grid. The produced hydrogen is then proposed to be used for energy production in the northern communities.

2.2.1. Hydrogen: Generation & Usage

Unlike the prior generation methods which utilize the various facets of the weather to generate electricity, hydrogen power uses hydrogen as a storage of energy. Hydrogen is not a renewable resource as it does not occur as H_2 gas in nature, instead it can be generated through the splitting of water [32] among other generation methods such as thermolysis of fossil fuels, photocatalysis, and bio – photolysis steam methane reformation which produced 50% of the worlds hydrogen [33] although it emits carbon dioxide. For the purpose of this study, the clean production and use of hydrogen will be explored and is proposed to be generated through the use of excess power from the southern grid system. One of the major drawbacks of hydrogen generation is the lack of infrastructure for production, currently the majority of the world's hydrogen (50%) is produced via steam methane reforming [33], which itself emits carbon dioxide. Further upgrades in clean hydrogen generation capabilities, such as the thermochemical copper-chlorine cycle [34], can result in cleaner energy generation through hydrogen method. This project will explore the production of hydrogen from electrolysis through excess grid energy.

2.2.2. Fuel Cell & Electrolyzer

Fuel cells are used to generate electricity from the potential chemical energy with a fuel. They are composed of three primary components: a cathode, anode, and an electrolyte, these components are necessary for the chemical reaction of the fuel to take place. The cathode and anode are electrodes where the reduction and oxidation reaction of the fuel occurs. Figure 8 shows the components and operation process of a Polymer Exchange Membrane (PEM) fuel cell.

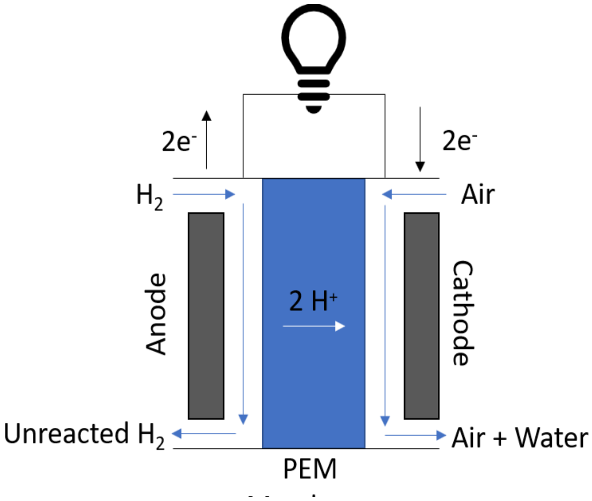


Figure 8 P.E.M. Fuel Cell Diagram

The use of hydrogen to generate electricity is performed using a PEM, with a Nafion™ polymer membrane, which allows for the transport of a proton to the cathode and also prevents the unwanted transfer for hydrogen gas and air to the wrong electrode in the fuel cell. Fuel cells require the input of a fuel at the anode and a secondary fuel at the cathode end. Hydrogen gas (H_2), which is the fuel, is fed into the anode, where it is oxidized and breaks down into two hydrogen ions (protons) and two electrons. The electrons are picked up by current collectors, which are connected to an external circuit, while the protons move across the electrolyte, or in some cases a membrane, towards the cathode [35]. Equation 1 & 2 shows the half reactions that take place at the anode and cathode of the fuel cell.

$$H_2 \leftrightarrow 2\,e^- + 2\,H^+ \tag{1}$$

$$2\,e^{-} + 2\,H^{+} + \frac{1}{2}O_2 = 2H_2O \tag{2}$$

At the anode, the fuel (i.e. hydrogen) added undergoes oxidation and loses an electron. The electrolyte is present for the transport of the ions, in this case the hydrogen without an electron (i.e. a proton) to the cathode. The electron passes through a connected circuit to generate a current and power an added load. While hydrogen is being added to the anode, air is added to the cathode, where the oxygen within air gains the electron that was lost by the hydrogen. Upon the transfer of the proton across the membrane it reacts with the ionized oxygen in the air to produce water, completing the chemical reaction. The fuel cell used in this analysis is the PEM fuel cell, named for its use of the proton exchange membrane in place of the electrolyte [36]. Electrolysis works in reverse, whereas in the fuel cell the addition of hydrogen and air produces electricity, in an electrolyzer the addition of electricity and water produces hydrogen and oxygen. The fuel cell allows for the conversion of the excess and curtailed energy stored in the hydrogen to electricity that can be used by the remote community.

Figure 9 displays the potential production of hydrogen gas from excess grid power throughout the year that can be produced using an electrolysis unit. The operating conditions of the 1 MW electrolyzer from Hydrogenic and the excess power values obtained from the IESO website [22] are used to determine the quantity of hydrogen produced per year. It is clear from Figure 9 that the excess electricity from the major grid can be used to produce millions of tons of hydrogen. The generation via an electrolyzer and consumption of hydrogen through a PEM fuel cell would yield a 35% conversion [27].

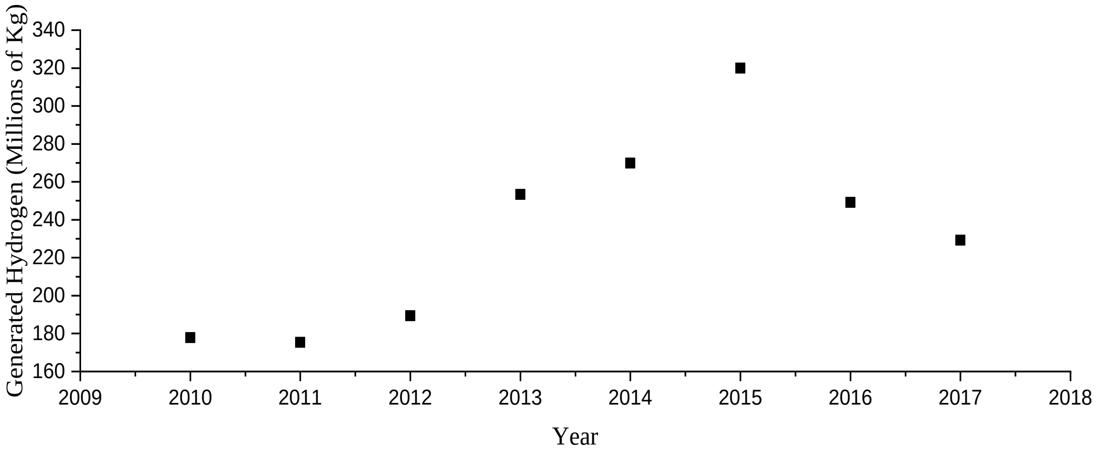


Figure 9 Hydrogen Production from Excess Grid Energy

To propel the hydrogen economy and make it feasible for hydrogen to be used as an energy carrier, options for storage must be explored. One method to store hydrogen is in the form of liquid or gas and typical storage methods include tanks or in large quantities in salt caverns [37]. Another method of storage is through hydrogen absorption, which utilizes the van der Waals bonding of hydrogen molecules by absorption into various materials. This process is achieved by utilizing various absorptive materials at high pressure and large surface area to bond hydrogen molecules to the porous material, typically carbon based [38]. The last method of hydrogen storage that can be explored is through chemical storage, which as the name suggests, stores hydrogen through a chemical reaction through the production of hydrides which can be broken down into two subgroups: metal and chemical hydrides. Metal hydrides work by reacting hydrogen with a base metal and producing a metal hydride compound, where the release of hydrogen is done through the addition of heat via thermolysis or though the addition of water through hydrolysis [37]. Chemical hydrides, similar to metal hydrides, store hydrogen through a chemical reaction of hydrogen with other elements to produce a chemical compound such as methanol or ammonia which allow for easier storage [37]. Much work is being performed in this field and can benefit the communities as transportation of produced hydrogen is an issue that needs to be resolved.

2.3. Renewable Energy

2.3.1. Wind Energy

Turbines have been constantly evolving and increasing their output through new developments in material engineering resulting in larger turbines. Currently the biggest turbine that is available for use on the market produces 6 - 12 MW of power [39]. Turbines are typically used in multiples to form a wind farm to deliver large magnitudes of power. Due to the short time to operation, with prevalent wind resources, the turbines have a distinct ability to follow the grid meaning that they can be turned on when the demand increases, and the grid requires more power. This makes them an ideal choice for producing power during peak loads. Another major advantage of these turbines is that during their operation they emit zero greenhouse gases during operation, and thus do not contribute to climate change. The primary components of the wind turbine are the rotor, hub, drive train, generator, control, tower and electrical system [39]. The rotor is typically a combination of three turbine blades designed to harnesses the kinetic energy of the wind through lift that is produced by the wind as it passes over the airfoils. Due to the profile of the airfoil sections which comprise the blade the fluid conditions result in a low velocity – low pressure zone on the suction side of the airfoil and a high velocity – high pressure condition on the bottom zone, which causes a lift force in the direction of the low pressure resulting in the airfoil moving upwards [39]. The resulting lift enacts a torque on the shaft to which the blades are connected. Kinetic energy is then transferred along the primary shaft to the generator through a gearbox. The gearbox is used to speed up the low frequency primary shaft to a higher frequency secondary shaft which transfers the rotational energy to the generator which subsequently converts the kinetic energy to electricity. Wind turbines typically operate in a range of wind velocities, they begin producing power at a "cut – in" speed and shutoff at much higher "cut – out" speed. The cut – in and cut – out speeds are typically 2.7 and 20 m/s respectively [39] and the "cut – out" speed is introduced to prevent turbines from harm caused by extreme wind conditions.

The zero emissions during operation from wind turbines make them a clean and green alternative to diesel generators. One of the drawbacks of the use of wind turbines is the generation of unwanted noise which occurs during their operation. Noise occurs due to both mechanical and aerodynamic reasons [40].

The mechanical noise [41] is a result of the various moving mechanical components such as cooling fans [37, 38]. The aerodynamic noise is a result of the wind that passes over the airfoils. In many cases, the noise adversely affects residents through general annoyance and sleep deprivation and reduces the quality of life [39 – 41] . In a remote community geological conditions such as trees and mountain ranges may reduce the impact on the community [47]. This may factor into the selection of renewables in a smaller community, as their proximity to the community may result in unwanted noise pollution.

2.3.2. Solar Power

Solar panels generate electricity by converting the sun's solar radiation to electricity. The panels utilize the "photovoltaic effect" where the exposure to light generates potential difference between two semi-conductor layers. The panels contain a p-type and an n-type semiconductor which produce a potential based on the solar radiation. The completion of the circuit by the addition of a load allows for the flow of current. Solar panels, unlike wind turbines, are not an active method of power generation as they do not have any moving parts, although some do rotate along an axis to face the sun; thus, the required manpower for maintenance and operation is much less. One disadvantage to solar panels is the weather as winds and snow can cover the panels area, reducing the efficiency of the panels. Panels are constructed of various materials: crystalline silicone (monocrystal, multi-crystal, and amorphous silicon), cadmium telluride (CdTe), cadmium sulfide (CdS), copper indium gallium selenide (CIFS), and gallium arsenide (GaSA) [48], each with different electrical efficiencies and costs, with monocrystalline and polycrystalline silicone being the highest efficiency. The effect of temperature is quite prevalent on solar panels as a decrease in temperature allows for greater efficiency [49]. One of the drawbacks of the panels is the space required for their deployment, to generate a large amount of power they require a large surface area, for the panels to have exposure to solar irradiance. The manufacturing of the PV panel cell material also results unwanted emissions and pollution, see LCA section 4.2.

2.3.2. Remote Communities Application

There has been prior work done to explore the potential of renewable energy (RE) production methods in remote communities and such of the work utilizes various software programs such as Renewable Energy Technologies Screen, and HOMER to explore various communities. Arriaga et. al. [9, 46] explored the community of Kasabonika Lake First Nation, which, like many similar communities, is supplied primarily by diesel power. The paper lays out the communities current and future demand, to determine the size of the energy generator. This paper proposes to supplement the existing diesel generators with an energy blend of solar and wind and analyzed the size of energy blends by their economic costs, resources availability, and operational capability. One of the major barriers to the adoption of RE technologies in remote communities is the cost of implementation and determined that wind has a high potential for RE penetration due to the availability of wind resources but has drawback due to high cost.

RE projects have been implemented in three communities within Ontario: Kasabonika Lake [51], Fort Severn and Big Trout Lake [52]. The community of Kasabonika Lake utilizes three diesel generators with a combined output of 2000 kW along with a smaller output by three 10 kW wind turbines. The community of Fort Severn utilizes combination of solar and wind in conjunction with diesel is implemented by the communities. The community has a supply of 300 kW solar, 10 kW wind, a 300-kWh battery storage to provide grid flexibility, with a back of diesel generators. Due to the availability of many water systems, many communities can utilize hydroelectric dams to generate power.

2.3.3. Cost

RE production methods have the potential to be much cheaper than diesel technologies and as their name suggests, generate energy from resources which do not dissipate over time [49, 50], which include the use of solar, wind, and hydroelectric power. Due to the numerous advancements in both price and efficiency, clean energy methods have become more viable choice [55]. Subsidized implementation, and the use of large-scale generation site have led to an overall cost effectiveness of renewables [52, 53]. Wind energy has a typical generation cost of 0.07 to 0.16 $/kWh [58], while solar panels have led to a production price close of 0.03 to 0.05 dollars per kWh. The price benefit of renewables provides an incentive to switch to renewables and has led some remote communities to explore renewable energy pilot projects. Sandy Lake paid 1.51 $/L for diesel in 2016 and consumed roughly 3.7 kWh/L of fuel, this conversion would lead to the price of 0.41 $/kWh as the cost of energy for the community, with subsidized costs to the communities averaging 17 cents per kWh.

2.4. Exergy Analysis

Exergy is defined as the useable amount of work that can be obtained from a system. Prior work done in the field of resource analysis via exergy analysis was performed by Le Corre et. al. [59]. The paper explored the quality of energy present in the wind and solar resources over Europe. It utilizes pre-developed exergy models for solar and wind resources, along with data obtained from the Department of Energy (DOE). The work developed spatial-temporal energy and exergy maps over the European landmass. It used wind data obtained from various weather stations to develop the wind exergy maps after analyzing the data by well-established formulas to determine the resources exergy quantities. The exergy quantities were compared with energy production quantities that would be obtained from the installation of wind turbines and solar panels in those regions to provide the exergy efficiency. Similar work was performed by Asgari et al. [60] focused on the exergy efficiency of a Bergey Excel – S wind turbine in the city of Tehran, Iran. The study utilized weather data during the course of a year to determine the exergy efficiency of a turbine and used a genetic algorithm to determine the optimal efficiencies. Exergy efficiency will determine the energy blend that will require the least amount of equipment to generate the most amount of energy thus saving capital cost and reducing emissions from the production of the RE blend.

Some gaps were identified in the literature review are as follows:

- Current site assessment methods do not consider the emission of greenhouse gases during the operation of the power plants
- Exergy analysis is not implemented in the assessment of remote community natural resources
- Fuel blend based on the available resources for seamless power generation in remote communities are not provided

Hence, the objectives of this research are to tie resource use and emission to allow communities to extract the maximum energy from natural resources and limit the emissions of greenhouse gases during the implementation of renewable energy. An exergy analysis is implemented on the selected renewable energy and the energy blend is affirmed based on a lifecycle analysis.

Chapter 3 – Methodology

To fully develop the energy blend that will benefit the community, the following two criteria are used: exergy efficiency and greenhouse gas emissions. The choice of two selection criteria allows for the determinization of a blend, one criterion would only provide one energy production method and not a blend, two selection criteria produces a blend which provides a balance between high exergy efficiency and low greenhouse gas emissions. The method is broken down into two major components, the combination of which is used to determine an energy blend for the remote community in question. Implementation of this methodology will result in the development of an optimized energy blend that reduce the raw material required to generate electricity, resulting in cleaner energy for the community. The two methods will explore the efficient use of resources available to the community and the emissions of the raw feedstock material into constructing the RE technologies. Resource assessment was performed through the use of exergy analysis on all three energy sources: wind, solar, and hydrogen. Exergy is defined as the maximum amount of usable work in a system [61] and is dependent on the kinetic, physical, and chemical properties of the resource. In the case of wind, it is defined by the velocity, the humidity content, the pressure and the specific heat [59]. For solar energy, it is defined by irradiance (solar radiation), ambient temperature, electrical efficiency, and the temperature coefficient of the solar panels. Exergy for the hydrogen fuel cell depends on the chemical properties of its components, meaning that the hydrogen fuel and air will qualities will be assessed [62]. Exergy efficiency will provide a measure of how well the systems utilize the energy resources that are present in the location and compare that to the electricity produced from the resources. The implication of a higher exergy efficiency is that for the same amount of energy converted, the method of conversion with the highest degree of exergy efficiency requires less resource input, such as units constructed, and fuel consumed. As the resources are converted to electricity by the RE technologies, the quality of those resources is reduced (i.e. as wind is used to generate power it slows down) meaning the quality of resources is depreciated which is known as exergy destruction. The analysis considers the generated electricity to the quantity of exergy that is destroyed and provides a more accurate efficiency of the system than an energy efficiency analysis as it considers the maximum usable energy. To carry out this analysis weather data obtained from local weather stations will be used to analyze the quantity of wind resource available to the communities. Many communities require fuel transported in by air and hence, have airports, which is generally the location of the weather station as is the case with the Sandy Lake community. Temperature, humidity, wind velocity, and pressure data are stored on Environment Canada repositories that are available to the public, which was extracted for the purpose of this study.

3.1. Exergy Analysis of Clean Energy Production Methods

3.1.1. Wind

To determine the exergy efficiency for the wind turbine a sample turbine is selected, as it would provide the energy value that can be produced with respect to wind velocity. As the community only requires 2.5 MW of energy at peak power, a smaller 25 kW turbine was used in a wind farm configuration to power the community. The selection of a smaller 25 kW wind turbine was done to easily compare with solar cells and fuel cells of a similar power rating, although the analysis can be carried out for other sizes. The typical 25 kW turbine has a swept diameter of 12 meters, a cut-in speed of 2.5 m/s, a rated speed of 11 m/s, and a cut-out speed of 25 m/s. Figure 10 shows the production of power at alternating wind velocities for a 25 kW wind turbine, taken at 15°C. The measured temperature was taken by a weather station and typical meteorological measurements are taken 10 meters above ground, since the turbine is 20 meters above ground a velocity adjustment was made. The log law [63] was utilized, and the surface roughness used was based on the location of the weather station, which was an airport.

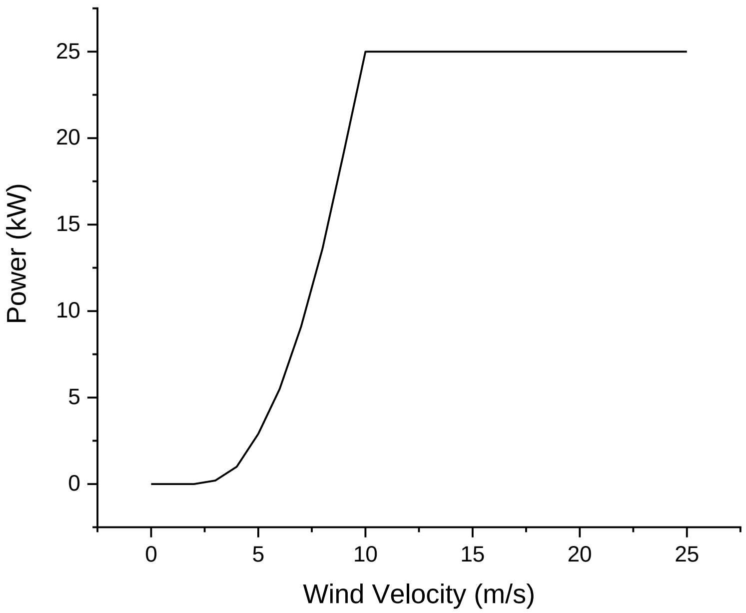


Figure 10 Wind Turbine Power Curve

The analysis can be performed with any sized turbine, as the energy generated and the mass flow rate of wind through the turbine area can be scaled up as the exergy destroyed and the power produced is dependent on the quantity of wind flowing through the wind turbine. The following model is used to determine to predict the exergy efficiency of the wind turbine during its operation in the community. The thermodynamic exergy value of the wind is a sum of the chemical and physical exergies which depend on the ratios of temperatures and pressures of the wind as it enters and exits the turbine with respect to the dead state or ambient values. The temperatures and pressures change as the wind is slowed by passing through the turbine implying a change in exergy. The physical exergy of the wind is the amount of work that can be done prior to the wind reaching equilibrium, hence the chemical exergy is a function of the temperature and the pressure, and the reference pressure and temperature is the ambient. Reference temperature and pressure used for this analysis is the ambient temperature and pressure of the environment, as the inlet and outlet pressures and temperature will come to equilibrium with the environment. The thermodynamic exergy is the sum of the physical and chemical exergy and represents the amount of potential work that can be achieved from the wind. Figure 11 details the change in wind quality, as the wind enters the wind turbine, part of that energy is used in turning the wind turbine and producing electricity. This results in a reduction in wind velocity, a variation in pressure, and subsequently a change in other factors which depend on the prior properties. A factor that is required in the determination of exergy is the temperature which depends on the velocity of the wind and the ambient temperature and is given by Equation 3 [64].

$$C_p T = C_p T_0 + \frac{V^2}{2} \tag{3}$$

When C_p is the specific heat capacity of air, T_0 is the stagnation temperature and V is the wind velocity. This temperature is used to determine the exergy present in the wind as its velocity changes as it passes through the turbine, however, windchill temperatures can also be used for analysis [59]. The use of stagnation temperature allows for the representation of the temperature of the wind as it undergoes thermodynamic changes while generating electricity. The stagnation temperature is determined for the inlet and outlet wind flows based on the inlet and outlet velocities of the wind. Figure 11 shows change in velocity and pressure of the wind as it enters and exits the wind turbine swept area, the components P & V stand for pressure and velocity, respectively. The subscripts 1 and 2 represent the inlet and outlet conditions of the wind, respectively

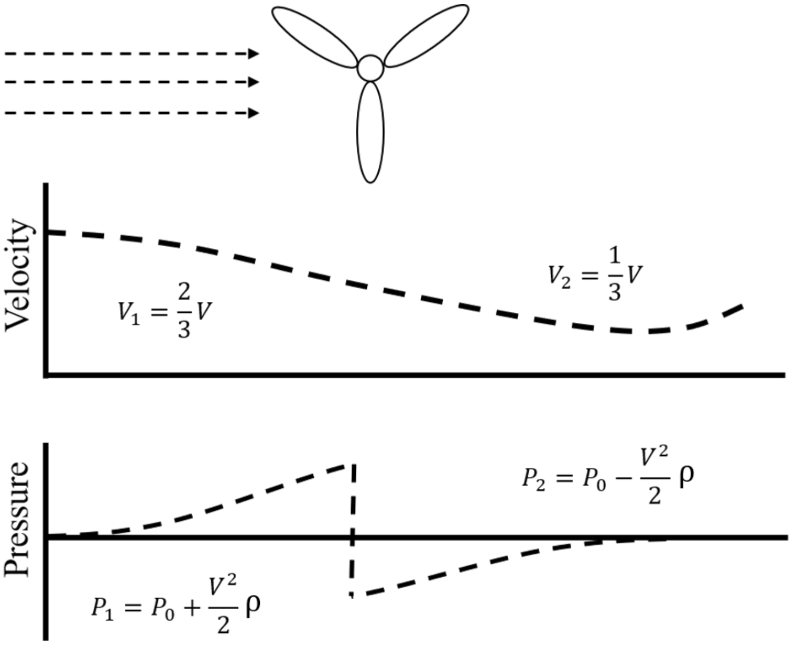


Figure 11 Wind Pressure & Velocity Profile (adopted from [65])

While the ambient temperature and pressure conditions are present in the data repository [66], the values at the inlet and outlet need to be obtained, using Equations 3 & 4 to determine the physical properties of the wind as they change over the wind turbine. P_0 is the atmospheric pressure, ρ is the density and V is the velocity.

$$p = p_0 \pm \rho \frac{V^2}{2} \tag{4}$$

Kinetic exergy changes as the wind flows over the wind turbine, due to the velocity changes of the wind and as the wind flows over the airfoil, a portion of that wind is slowed down thus, the quality of the energy of the wind is reduce meaning exergy is destroyed. Changes in physical and chemical exergies are also calculated due to the change in pressure and temperatures of the wind, and Equations 5 & 6 are used to calculate the specific inlet and outlet exergies. Equation 5 is used to define the physical exergy of the wind with respect to mass, C_p is the specific heat capacity of wind, C_{pv} is the specific heat capacity of water, T is the temperature at the inlet, T_0 is the ambient temperature of the wind, R is the gas constant for air, p is the inlet pressure, p_0 is the ambient pressure and ω is the humidity ratio [59].

$$e_{ph} = (C_p + \omega C_{pv})T_0 \left[\frac{T}{T_0} - 1 - ln\left(\frac{T}{T_0}\right)\right] + (1 + 1.6078\omega)RT_0 \, ln\left(\frac{p}{p_0}\right) \tag{5}$$

Inlet chemical exergy is calculated using Equation 6, which has many of the same variables as the physical exergy.:

$$e_{ch} = RT_0 \left\{(1 + 1.6078\omega) \, ln\left[\frac{1 + 1.6078\omega}{1 + 1.6078\omega_1}\right] + 1 + 1.6078\omega \, ln\left(\frac{\omega_1}{\omega}\right)\right\} \tag{6}$$

The exergies specific exergies are calculated both at the inlet and out of the turbine to determine the change in quality in physical and chemical exergy of the wind and that is summed with the kinetic energy of the wind to determine the quantity of exergy destroyed as the wind generates power.:

$$\dot{E}x_{wind} = \Delta\frac{1}{2}\dot{m}V^2 + \dot{m}\sum e_{ph} + e_{ch} \quad (7)$$

To determine the exergy destruction and exergy efficiency of the complete system Equation 8 is implemented.:

$$\psi = \frac{\dot{E}}{\sum \dot{E}x_{Wind,des}} \quad (8)$$

3.1.2. Solar

Solar exergy requires the input of cell temperature, was obtained by the relation provided from Fouladi et. al. [67] and is based on the irradiance and the ambient temperature of the environment. Upon calculation of cell temperature, the electrical exergy values of the panel can be obtained by Equation 9.

$$\eta_{cell} = \eta_{ref}\left[1 - \beta\left(T_c - T_{ref}\right)\right] \quad 9)$$

Where $\eta_{ref}$is the reference efficiency, beta is the temperature coefficient [68], and T_c and T_{ref} are the cell temperature and the standard test temperature of the solar panel. The electrical exergy, Equation 10, of the solar panel is the product of the incoming solar radiation, the cell efficiency which is dependent on the cell temperature (T_{cell}) and solar radiation (S_t), and the solar panel area (A).

$$\dot{E}x_e = \eta_{cell}S_tA_{cell} \quad (10)$$

The next step to determine the solar exergy, or the quality of solar energy incoming to the solar panel, as this is the theoretical maximum energy that can be generated by the solar panel. It can be noted from Equation 11 that the solar exergy is dependent on incoming solar energy, S_T, the ambient temperature, T_{amb}, the surface temperature of the sun T_{sun}, and the area of the solar cell A_{cell} [59].

$$\dot{Ex}_{solar} = S_T\left(1 - \frac{T_{amb}}{T_{Sun}}\right) * A_{cell} \tag{11}$$

Finally, to determine the solar exergy efficiency, the electrical and thermal exergies are summed and divided by the incoming solar exergy (Equation 12).

$$\psi_{eff} = \frac{\dot{Ex}_e}{\dot{Ex}_{solar}} \tag{12}$$

As the exergy equations required operational values of manufactured solar panels, a panel was selected whose specifications were used in conjunction with the above formula to determine the efficiency. The required value of the electrical efficiency and surface area were determined from the panel's mechanical specification sheet [69]. Efficiency data was then average monthly, while the solar panels were theoretically producing power. Solar irradiance and temperature data for solar exergy efficiency calculations were obtained from the Photovoltaic Geographical Information System (PVGIS) provided by the European Commission [70]. The data obtained was used to determine the thermal exergy and the total irradiance available to the region. To simplify the analysis, the solar panel was assumed to be a 2-axis system meaning it can swivel in all directions to face the sun's rays for improved performance.

3.1.3. Fuel Cell

Unlike solar and wind-based energy generation methods, hydrogen fuel cells do not depend on weather. The PEM fuel cell is instead dependent on the support systems which allows it to operate [62]. The cell does not utilize the natural wind and solar resources and is thus independent from weather conditions. The exergy of the fuel cell is calculated by determining the physical and chemical exergies of the products and the reactants streams of the fuel cell [66, 67]. Due to its operation within a contained system, the various temperature, wind, and solar conditions of the environment cannot impact the operations of a fuel cell, instead the fuel and oxygen is fed into the cell and are conditioned by supporting fuel cell equipment. To obtain data for this analysis, prior published work is used to obtain the operating data of a 21 kW Ballard fuel cell system [71]. During the operation of a PEM fuel cell, hydrogen and air are added as reactants whereas unreacted air, excess hydrogen and water are emitted as products as a result of the chemical reaction. The exergy destroyed is dependent on the product that is consumed, in this case hydrogen and oxygen, that will result in the production of electricity and water. Thus, to calculate the exergy destroyed, the exergies of the products and the reactants must be calculated, and the exergy destruction is the exergy of the product minus the reactants, as shown in Equation 13.

$$E\dot{x}_{FC} = \left(Ex_{ch} + Ex_{ph}\right)_{prod} - \left(Ex_{ch} + Ex_{ph}\right)_{rect} \tag{13}$$

Equations 14 & 15 specifically represent the models employed to determine the physical and chemical exergies, respectively, and importantly the exergies are a product of the mass flow rates of the chemicals being added to the fuel cell and those being produced, with respect to their specific exergies. Where the physical portion exergy of the reactants and products is determined using Equation 14.

$$\dot{Ex}_{ph} = \dot{m}\left(C_p T_0\left[\frac{T_2}{T_0} - 1 - ln\left(\frac{T_2}{T_0}\right)\right] + (1 + 1.6078\omega)RT_0\, ln\left(\frac{p_2}{p_0}\right)\right) \tag{14}$$

It is noted that the physical exergy takes into account the temperatures and pressure inputs of the fuel, air, water, and excess air in the exact same method as the physical exergy equation used in the wind turbine exergy analysis. The chemical exergy is determined from Equation 15, where R is the universal gas constant, T is the temperature, e_{ch} is the specific chemical exergy of the various elements obtained from literature and is dependent on the mass flow rate of reactants and products.

$$\dot{Ex}_{ch} = \dot{m}(x_n e_{ch} + RT \sum x_n\, ln x_n) \tag{15}$$

The chemical exergy for air is determined by the weighted chemical exergy of its individual parts: 21% oxygen, 70% Nitrogen, and the remaining elements, and the variable x_n in the equation is the molar fraction of those individual components. The mass flow rate of the products is dependent on the reactants and the power being produced by the fuel cell. Finally, determining the exergy of the products and subtracting the reactants exergy determines the exergy destroyed by the power generation process. Determining the power produced from the Voltage-Current curve provided by the manufacturer (Appendix) determines the power produced with respect to the current and dividing that value with the exergy destroyed determines the exergy efficiency and it is given by Equation 16.

$$\psi_{ex} = \frac{\dot{W}}{\sum \dot{E}_X} \tag{16}$$

The power output is the net power of the fuel cell, it accounts for the ramp up in the energy demand with respect to the increase of the load by the various support systems. Flow rates of the fuel cells can control the power produced by the cell; thus, a proper configuration of a fuel cell system can allow it to operate at a maximum efficiency, something not achievable by wind and solar power production methods.

3.2. Life Cycle Assessment

Total greenhouse gas emissions can be calculated by using the current and projected power demand and the typical lifetime of the energy resources. An life cycle assessment is used to determine the input and output material flows into a system or product over the course of its life and is defined by the International Organization for Standard and is laid out in the ISO14040 [73], Figure 12. The results of the analysis show the energy required during the production of a product, the number of raw materials going into producing the product, and the resultant energy and raw materials from the recycling, if possible, of that product [74]. For the purpose of this research the GHG assessment is performed on clean energy generations methods: wind turbines, PV panels, and the PEM hydrogen fuel cell, to determine the method with the lowest greenhouse gas emission, primarily CO_2. The limitation of not considering operation and disposal phase, is made as the operations and disposal of the system were not as significant as the emissions from the raw feedstock material. The analysis is done through compiling data obtained from published literature which follow the guidelines laid out by the ISO. The analysis provides the energy inputs and emissions, obtained from published data, for various raw materials for the energy generation methods.

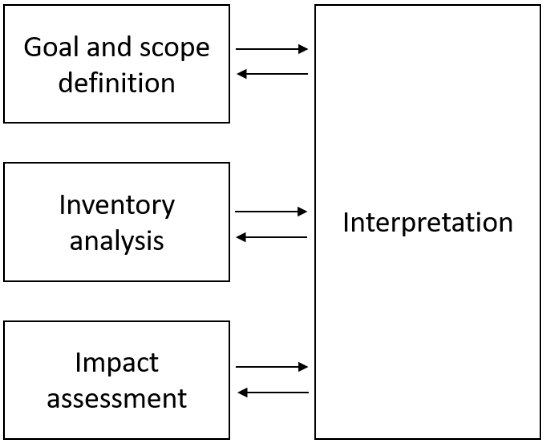


Figure 12 Life Cycle Assessment Framework

It is key to establish a goal and scope of the life cycle assessment [75] based on the problem that is being solved by the LCA. For the purpose of this project the life cycle assessment is being used to determine which energy production method produces the greatest amount of energy with the smallest amount of greenhouse gases emitted. The key metric used to compare the energy sources will be the Global Warming Potential (GWP) of the energy sources and, as the name suggest, it explores the emissions from the feedstock during the construction, maintenance, installation, and decommissioning of the energy production methods, although the scope of this research will limit the GWP to emissions from the raw feedstock. The GWP will be quantified by the emissions of CO_2 with respect to the functional unit of one kW. This definition can help narrow down the scope and produce the other criteria used in developing an energy blend. The GWP does not include the transportation or construction aspects of the power plant, as the transportation of equipment and other emissions for construction are similar and essentially a common denominator. Thus, the analysis is normalized with respect to the size of the power plant and each of the three energy methods can be compared directly.

The next step of the analysis is to conduct an inventory analysis that explores the various raw material feedstock input into the energy system. The inventory analysis is used to determine the carbon dioxide output during the production of the raw material, and thus the total emissions from the production of the final energy production device. The majority of this data is obtained through published literature [70, 71], as the values for emissions for feedstock are well established. An issue that arises in this method is the determination of the raw material input into the energy production method, the construction and masses of each component are typically kept proprietary by manufactures through “trade secrets” and are thusly hard to determine. Similar to the construction methods and feeds, maintenance schedules and products were also challenging to find hence, to carry out this portion of the LCA, published findings and data were used to determine the output values.

Finally, the impact assessment is the last part of the LCA framework, which ties back to the goal and scope definition. The impact of the energy systems on the environment will be quantified via the emissions per kW of energy rated to be produced, this is the functional unit for this study. The justification of this method is that this value will be used to develop the energy blend when used in conjunction with the exergy efficiency value. Although, there may be the emissions or production of toxic substances during the production of RE technologies only carbon dioxide emissions will be used for the energy blend development. In conclusion, the combination of the GWP and the peak exergy efficiencies will be used develop a blend that will be recommended to be constructed for the community.

Chapter 4 – Results & Discussion

The Results and Discussion section is broken into two portions, one focusing on exergy analysis, section 4.1, and the other focusing on renewable energy potentials in remote communities, section 4.2. The implementation of renewable energy systems will help reduce the emissions of the communities during power generation and reduce emissions during the production of electricity and allow communities to continue to grow.

4.1. Exergy Analysis

To determine the clean energy generation method for the community, the natural resources available to the community will be analyzed and the proposed method to accomplish it is through an exergy analysis. The analysis explores the quality of the resources and how well the resources will be used when generating electricity. An exergy analysis provides a comprehensive analysis of the resources' use and can be used to determine which energy method will generate the highest amount of energy from the least amount of resources, hence reducing the costs and limiting emissions from the implementation of an infrastructure project. The analysis provides the maximum possible useful work that can be extracted from a resource as it returns into equilibrium to its environment. The growth of energy infrastructure has the combined benefit to stimulate the community's economy, reducing emission, reducing Canada's dependence on fossil fuels, and limiting the adverse effects of climate change.

4.1.1. Wind

Figure 13 shows the monthly average of the data of wind exergy efficiency at the community from 2013 to 2018. Firstly, it is important to notice that the efficiency values are not constant throughout the year and vary during the course of the year. The monthly averaged exergy efficiency values ranged between 7 and 26 % from the data obtained during 2013 – 2018.

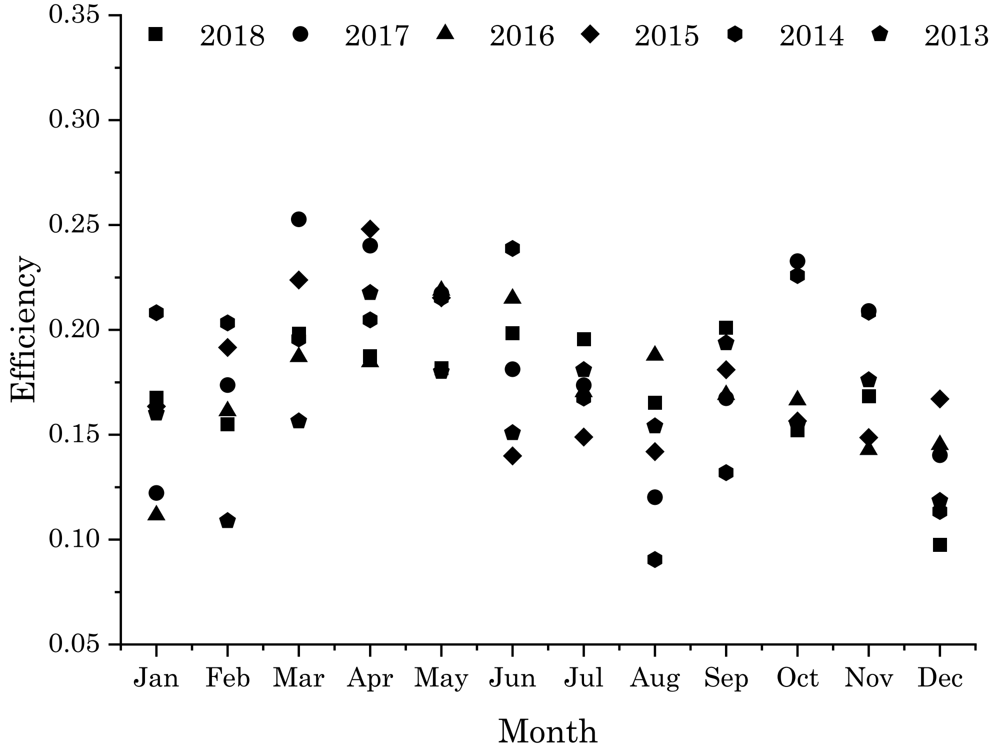


Figure 13 Wind Exergy Efficiency (2013 - 2018)

The low average efficiencies observed over the year resulted from the low wind velocity, see Figure 14, measured at the community. Importantly the average wind speed is below 13 km/h (3.6 m/s), which is close to the cut in speed of the wind turbine of 2.5 m/s. As such, due to low mean velocities of wind the community is not a suitable site for the placement of a wind turbine [78].

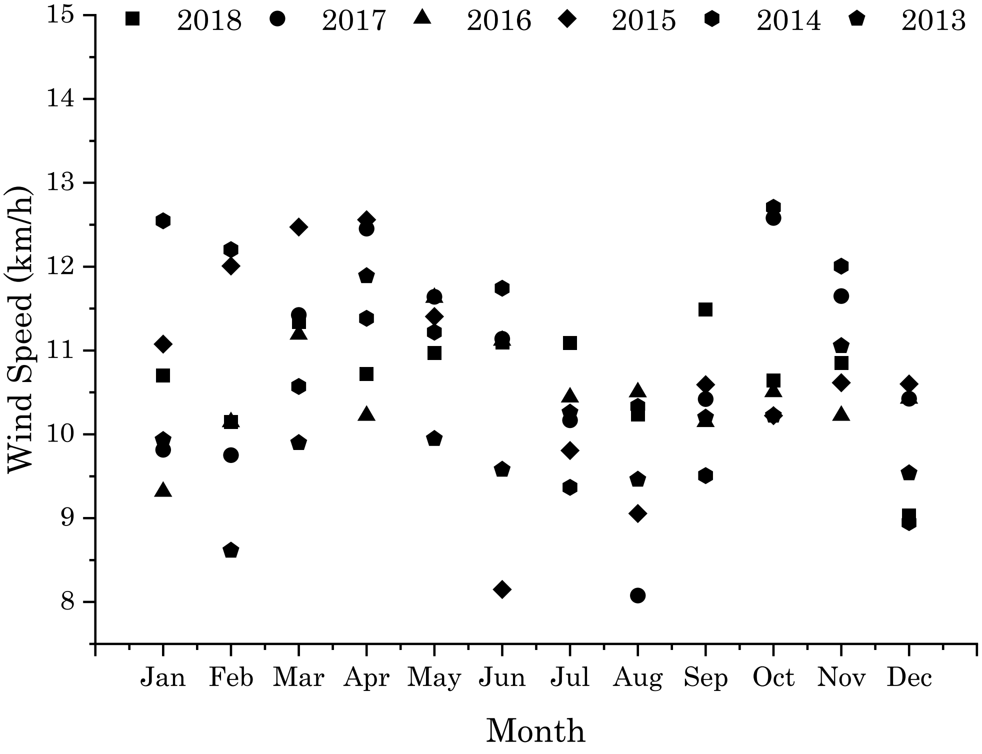


Figure 14 Average Wind Velocity (2013-2018)

As expected, there is a correlation of the efficiency to the wind velocity, Figure 15, shows the correlation ($R^2 = 0.65$) between exergy efficiency and wind speed meaning that as the velocity increase the exergy efficiency will also increase.

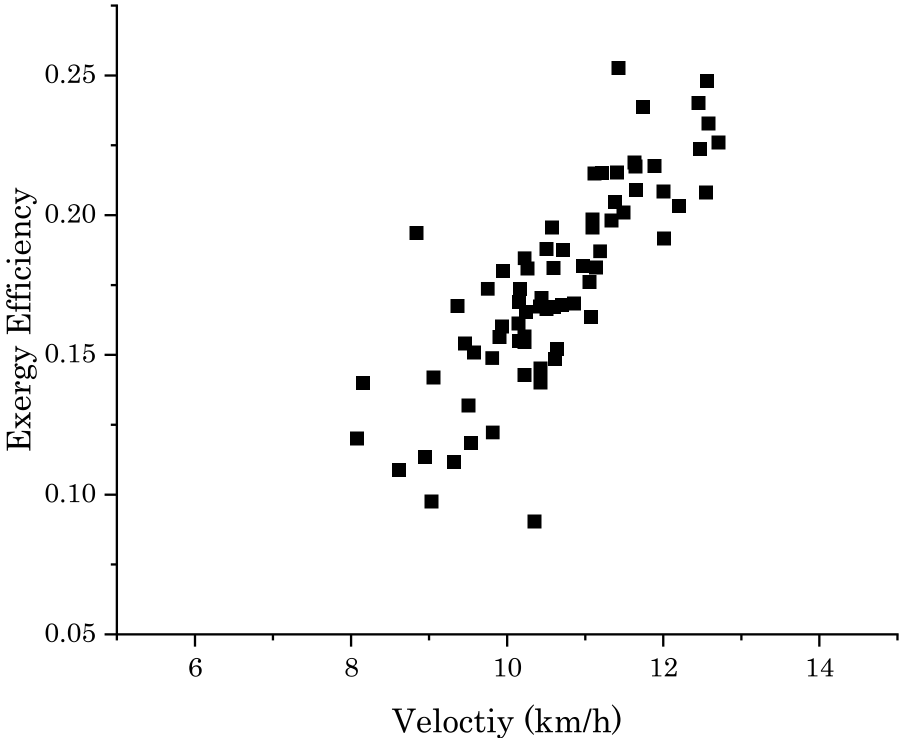


Figure 15 Wind Exergy and Velocity

The low efficiency due to the low energy availability will further impact the capacity factor of the wind farm, thus increasing the quantity of wind turbines required to generate adequate energy for the community. This further increases the emissions when developing a wind farm for energy production for this community.

4.1.2. Solar

Solar exergy efficiency can be observed over the 6 years in Figure 16. The plot shows exergy efficiency for individual year and the relationship they have with respect to time of year and it is observed that the exergy efficiency drops in the summer months. This is likely due to the electrical efficiency of the solar panels, which depends on the ambient temperatures and summer months with their highest temperatures result in the lowest efficiency values. This observation leads to allow designers to choose cooler environments for the application of solar panels, although solar irradiance is also lower in those regions. Furthermore, solar exergy do not vary much throughout the year, the efficiency varies from 17.5 to 20.5 %, with the highest efficiency in the winter months and lower in the summer, this is due to the temperature variance throughout the year, as the electrical efficiency is dependent on the temperature.

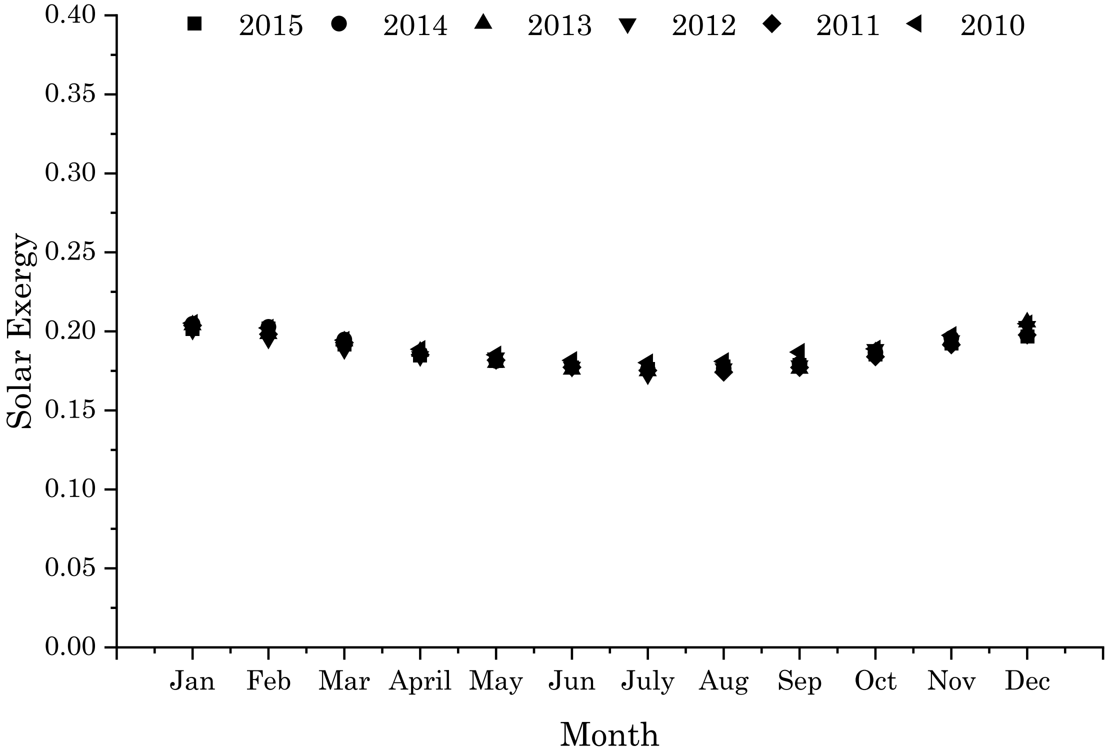


Figure 16 Solar Exergy (2010 - 2015)

The correlation between solar exergy efficiency and temperature was quite high ($R^2 = 0.98$), the negative correlation can be used to make use of solar panels more during winter months and to take advantage of the temperature effects. Furthermore, reflections from the snow can also positively impact solar energy production as the solar radiation is reflected back to the solar panels. A hindrance with cooler communities is the lack of solar energy, as observed in Figure 17. The PVGIS data obtained, shows the energy that can be captured during each month and is higher during the summer months. The data is based on the energy produced with a 2-axis solar panel, which moves to face the sun to capture the most energy. Due to the higher longitude of the community, lower energy would be captured during winter months.

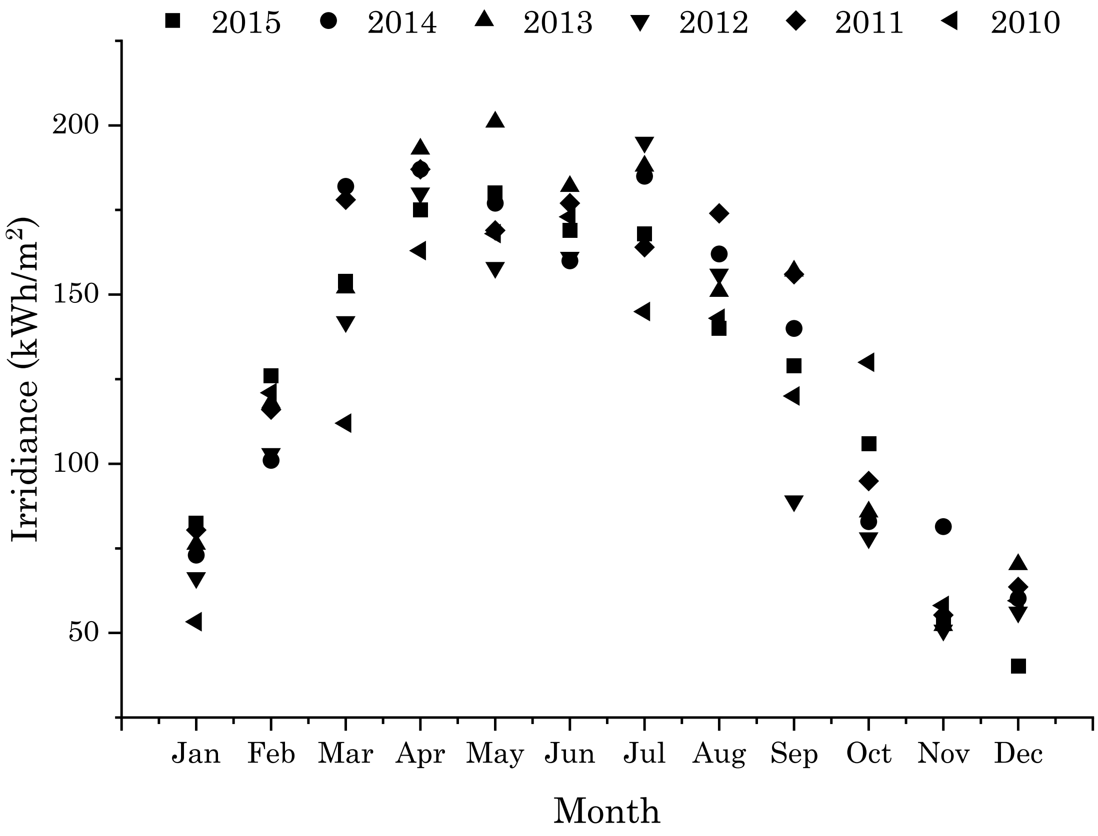


Figure 17 Average Solar Irradiance in Sandy Lake (2010-2015)

The low solar irradiance observed at the community would result in a higher land area usage to generate the electricity needed to power the community. Figure 18 compares the wind and solar exergy efficiencies over three years, as observed the wind exergy efficiency varies greatly throughout the year, while solar exergy efficiency remains constant throughout the year. Worst-case efficiencies are explored to size the blends and for wind and solar the efficiencies are 9% and 17.5%, respectively.

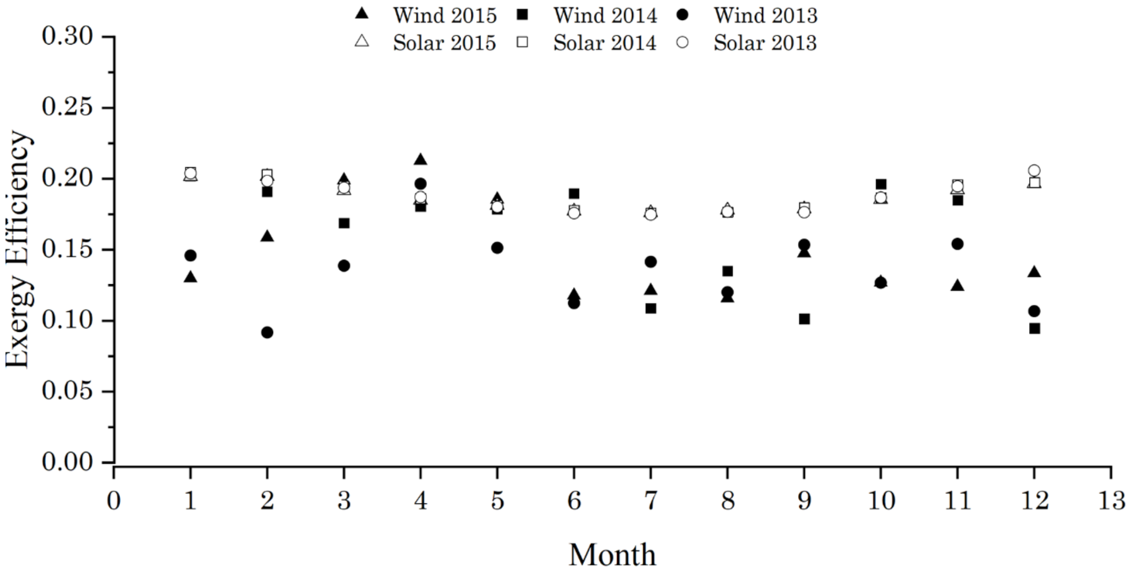


Figure 18 Combined Solar and Wind Exergy (2013 - 2015)

4.1.3. Hydrogen

To model the fuel cell, a prior published study [66, 74] was used to determine the fuel cell's operating conditions. Figure 19 shows the exergy efficiencies with respect to the current and the data was obtained from Rabbani et. al. [71]. It is of importance to note that the energy efficiency peaks around 50 amps whereas the exergy efficiency peaks at roughly 180 amps and the ability to select the current at which to operate the fuel cell for optimum efficiency allows for a reduction in the fuel needed to generate power. Additionally, multiple fuel cell units can be combined into a system that operates at the optimum energy level and since the Sandy Lake community requires a 2.5 MW power system, a 100% hydrogen system will consist of multiple 21 kW cells in a combined packaged unit. Furthermore, instead of operating all fuel cell units at variable currents, the system could switch off the excess fuel cells and operate the remaining ones at the optimum efficiency. This ability to fine tune efficiency cannot be achieved with the other energy generation methods. Additionally, unlike the other energy generation methods, the fuel cell is not directly affected by the temperature during operation, instead some of the power produced is used by the auxiliary systems to allow for optimal operation. The auxiliary systems contain pumps, radiators and other support components. The power consumption of these components is also modeled and is subtracted from the gross power production from the cell. The change in efficiency is due to the increase in thermal regulation and fuel supply demand during different power levels, that is why efficiency is lowest during low and high-power levels. As long as the proper configuration is being maintained, the fuel cell will operate at the correct power level and create the optimum amount of energy and utilize the fuel effectively. The fuel cell for the purpose of this study is being operated at the optimal current level (0.6 amp/cm^2 or 180 amp, operating at an exergy efficiency of 29%) level of 21 kW, to be comparable to the wind turbine. The power curve of fuel cells is typically linear with respect to current and as such the highest current drawn will result in the highest power produced. Further analysis can be done with manufacturer-based data to develop a more accurate understanding of the operating regimes of the fuel cell.

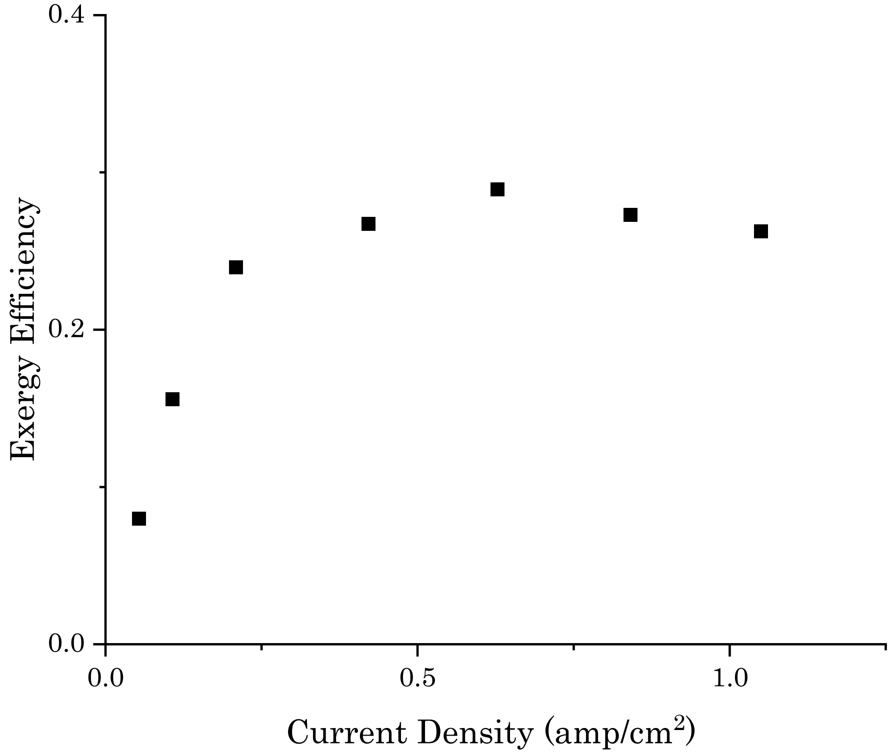


Figure 19 Hydrogen Fuel Cell Exergy Efficiency

The generation of hydrogen will have with it a destruction of exergy, as such the exergy efficiency of electrolysis is also considered. Typically, hydrogen production from electrolysis has an exergy efficiency of 67% [80], thus the maximum combined exergy efficiency of the electrolysis and electricity generation is 19.4%.

4.2. GHG emissions for Blends

As defined in the methodology the functional unit for the purpose of this analysis is the emissions of the production of raw material per kW of energy produced. Data for material breakdown of the RE technologies is obtained from literature as much of it is kept confidential and thus published and reviewed data is used. The LCA is defined by Figure 20 and will be conducted using the raw material input to produce the RE technology. The design lifetime of all the RE methods is 20 years and since some of the technologies have a shorter lifetime (i.e. PEM fuel cells) the final value will be multiplied by the quantity needed to complete a 20 – year lifecycle. This allows for the functional unit to remain constant throughout the analysis as the factor of lifetime is removed.

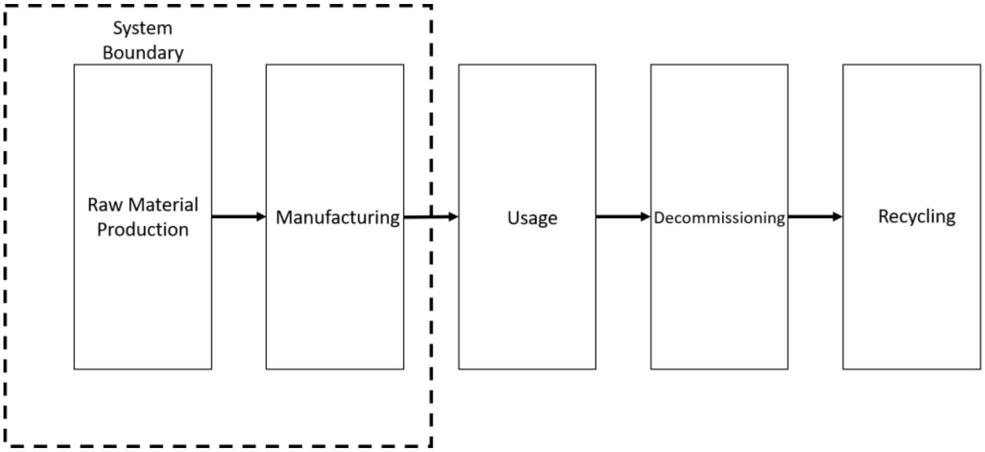


Figure 20 LCA Process Diagram

4.2.1. Wind

Turbines are constructed from diverse group of materials, from the concrete used in the foundation to steel used for the tower and the fiber glass used for the rotors [4]. All the materials require the input of energy to be converted to a usable form. The energy used to convert raw material into a useable product is known as the embodied energy and is a suitable metric to measure the efficiency of a power generation source. As a 25-kW wind turbine was analyzed for the purpose of the exergy analysis, although due to a lack of published physical specifications a similar, 20 kW, turbine is analyzed for greenhouse gas emissions. Typical wind turbines are composed of steel, fiberglass, copper, concrete, adhesives aluminum, and composite materials [81] and the their percentages of composition are provided below. This data along with turbine weights will be used to determine the quantity of emissions from the production of the raw materials and displayed in Figure 21.

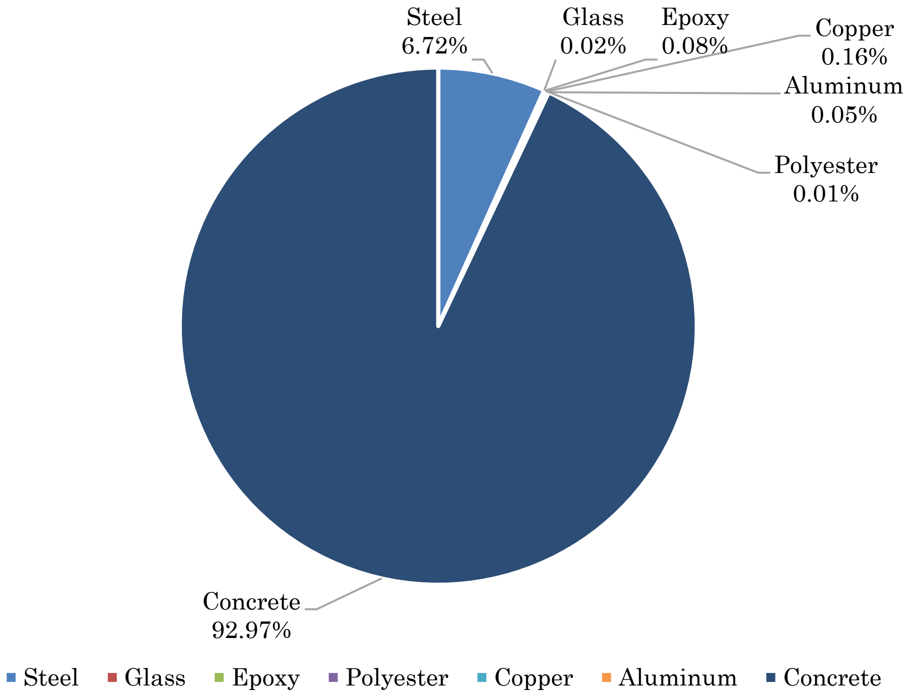


Figure 21 Wind Turbine Composition

The major components of turbines are rotor, nacelle, drive train components and tower, which are further broken down. The nacelle of the wind turbine is used to house the equipment necessary for energy conversion as it contains the drivetrain, gearbox generator shaft, cooling components, control systems and generator. High stresses occur on these components hence most of them are made of steel, aluminum, copper and plastics. The metallic components have potential of recycling upon the decommissions of the turbines, while plastic and composite components are less likely to be recycled. The rotor of the wind turbine consists of the turbine blades, hub, blade extender, and the pitch drive system. These components are typically constructed with fiberglass, balsa wood, polymer foams and held together with epoxy adhesives. The tower of the wind turbines is typically constructed with steel and concrete to build a secure foundation and is used to ensure the turbine is in the optimum wind profile region. It is also used at the housing for the transfer of power from the nacelle to the ground electrical unit hence, it has to be constructed robustly enough to ensure the turbine can function over the course of its lifetime. Since the exergy analysis of the wind turbines focused on a 25 kW, the GHG analysis should also focus on a similar sized turbine. As literature data for a 25 kW wind turbine were not available, a 20 kW wind turbine was selected and the values for raw feedstock consumption were obtained [77]. As observed in Figure 21 concrete is the most used material by mass due to its density and its requirement to form a strong foundation. Utilizing the preestablished rates for emissions of materials produced the combined emissions for the production of the raw material for a typical 20 kW turbine which yielded 21,690 kg of CO_2. Normalizing this value to allow for a proper comparison with other energy production methods provides a value of 1084 kg of CO_2/kW An important consideration is that this number relies on the assumption that the 20 kW turbine is used in the community, as these can be used readily implemented in remote communities [78]. These numbers do not display the GHG emissions during the maintenance and transportation of the turbines to the remote communities, or the emissions to construct the wind turbines at the location once the components arrive. This was done as all three methods would need to be transported and would essentially have similar emission profile during transportation. Maintenance is also omitted as different manufacturers have different maintenance regimes and the analysis is beyond the scope of this thesis. It is also likely not significant to the overall emissions impact.

4.2.2. Solar

For the purpose of this analysis, a polycrystalline photovoltaic panel is considered as it was used to conduct the exergy analysis and has the greatest global market share of the PV market [82]. PV panels typically are composed of the actual solar module and balance of plant material, which include mounting structures, inverters, cables and other connectors [83]. Balance of plant components can vary greatly in configuration due to the choice of installation hence, some communities may choose to mount panels on the roofs of local buildings, or they may choose to have a specific region that is designated as the generation station. Data from Xu et. al. [84] was used to develop the material flows model for the life cycle analysis. The primary energy generating component of the PV panel is the silicone cell. Silicone is typically obtained through processing of silica from sand that is converted to Silicon metal at a high purity in a furnace and it is obtained in the form of silicone ingots. Ingots are then further processed into smaller thinner wafers by cutting and the silicon wafers are treated by etching with acids to produce the final silicone cell. Silicon wafers are then sandwiched between layers of either plastic or glass to form the final silicone cells that are processed further and manufactured into PV modules with the addition of the support structure, inverter and connecting wires [85]. The production of the silicone is one of the primary means of greenhouse gas emission as it results in the production of more than 660 kg of CO_2 per kW during the manufacturing process [82]. The inverter of the PV panel system works to regulate the power being produced so that it can be fed into the grid [86], and it is typically constructed out of copper (wiring), aluminum, steel, printed circuit boards, and wiring components. The wires are typically produced of copper and coated in a polyvinyl chloride material (PVC). Copper manufacture is the primary emission of greenhouse gas at this stage. Figure 22 displays the mass distribution by the various raw materials and glass is the primary component of the panel as it covers the entire area of the silicone panel which is used to produce power. The base of the cell is typically constructed of aluminum and steel to provide support during various wind and weather conditions. From the data obtained from Xu et al. it can be determined that the greenhouse gas emission from the production of raw feedstock material for a solar panel is 861 kg of CO_2/kW_l.

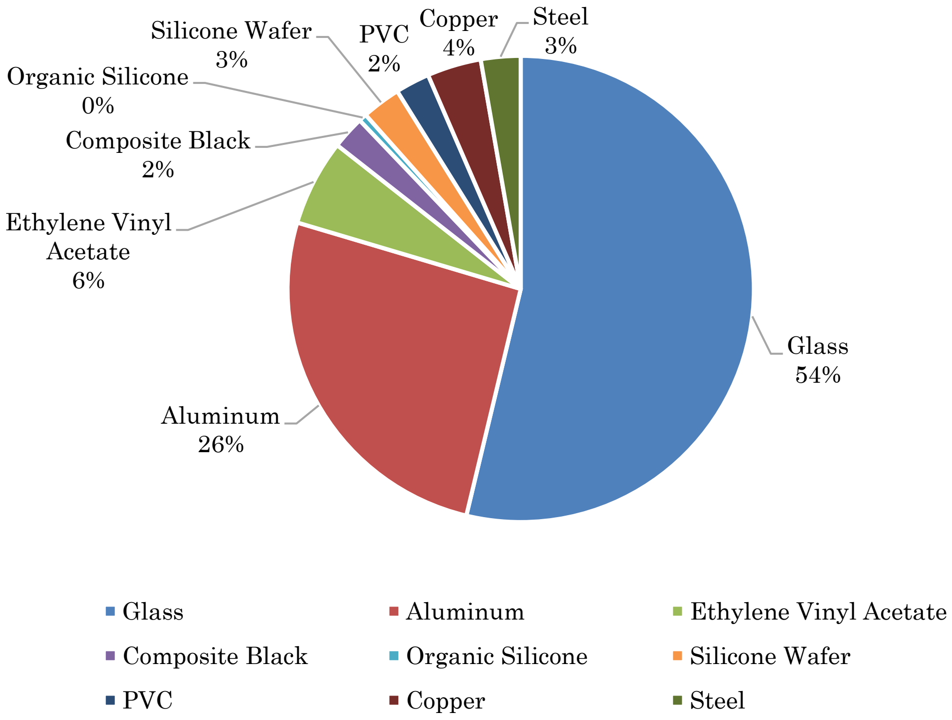


Figure 22 Solar Panel Composition

4.2.3. Hydrogen

PEM fuel cells require a few components for assembly such as graphite electrodes, PEM membrane, bipolar plates, catalyst layer, membrane electrode assembly (MEA), gaskets, end plates gaskets, and other major balance of plant systems [84, 85]. Much of the fuel cell composition data is proprietary information to allow companies to maintain industry competitiveness, thus a preestablished analysis was utilized. The report provided the data for the fuel cell at the established functional unit for a PEM fuel cell. This data was then compared with data for the emissions for greenhouse gases and the results were obtained. The raw material data for a fuel cell at the functional unit is provided and the individual components are broken down in Figure 23. This resulted in the total emissions of 47 kg of CO_2 / kW based on emissions data from [89], the value is low due to the fuel cells power density, a smaller 25 kW unit is much smaller than a 25-kW wind turbine or solar panel. One shortcoming that fuel cells face is their lifetime as it was determined that a typical fuel cell operating at maximum power would last 26,000 hours. This is not comparable to the 20 years of lifetime from wind and solar panels; thus, the values have to normalized to a 20-year lifetime, which means that the fuel cell is constantly replaced and that results to a higher emissions value of 461 kg CO_2/kW_{el}. This allowed for greater comparison to the solar panel and wind turbine. One of the most greenhouse contributing raw materials is the platinum [90] used as a catalyst, although there is very little in the PEMFC, as observed in Figure 23, below. Platinum does not occur in high quantities and thusly, mining for platinum requires a higher effort and more resources, resulting in a larger emission of GHGs. Although Platinum emits a large quantity of emissions during its production, its low use in the fuel cell does not greatly affect the over emissions of the fuel cell. The material that results in the most in the fuel cell is the graphite plates, which emit close to 4.9 kg of CO_2 per kg of graphite produced [91], (i.e. 46% of total emissions). Data for Nafion ™ was unobtainable likely due to it being a proprietary material. Due to their short lifetime PEMFC need to be replaced constantly, hence research is being performed to upgrade their lifetime to 40,000 hour which would make them more usable for stationary power generation [92]. This would allow fuel cells to be more appealing for energy production, more over the clean production of hydrogen is also being explored and work is progressing on that.

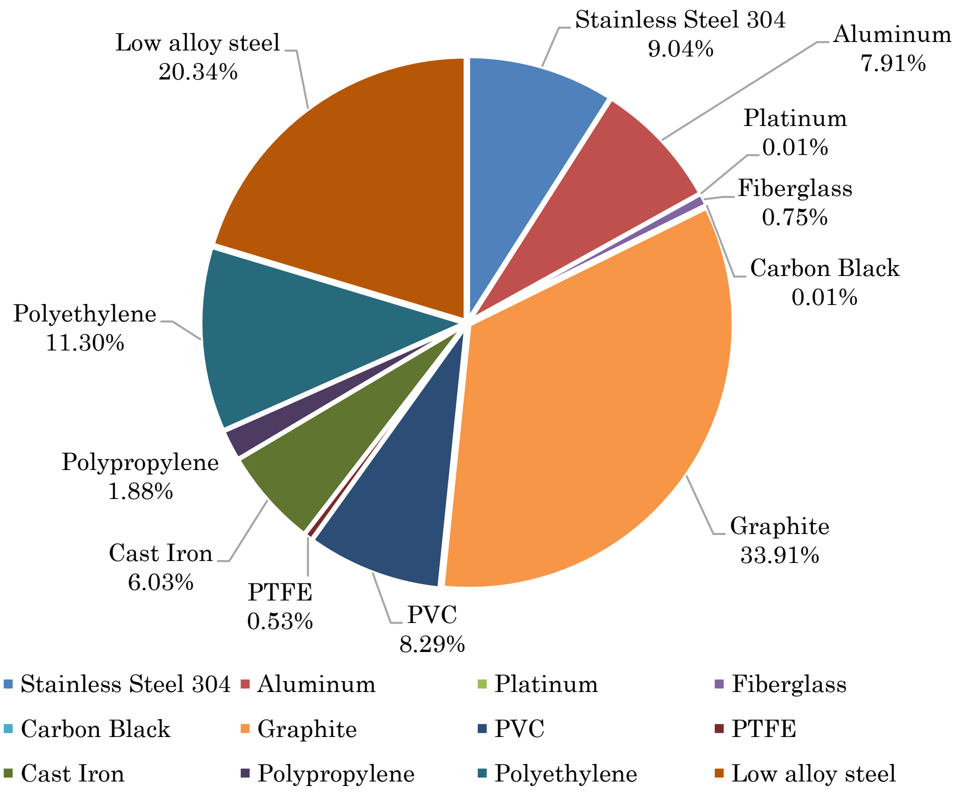


Figure 23 P.E.M. Fuel Cell Composition

Unlike wind and solar energy production methods, fuel cells require the constant transportation of hydrogen from the southern grid to the community. To model such a trip, current diesel transportation methods are explored. The transportation of diesel produced 16.9 tons of CO_2 in 2015 and was the result of 21 trips by road [93]. The community requires 12.4 million kWh of energy throughout the year, this would equate to 767 tons of hydrogen gas per year.

Current transportation methods can transport up to 1100 kg [94] per trip and assuming a similar emission rate as the diesel transport trucks the combined transportation of a year's worth of hydrogen would result in 767 tons of CO_2 per year. When this is adjusted over a 20-year lifetime and normalized with respect to 3050 kW (i.e. current station rating), which is the current power generation station rating, yields in additional emissions of 5030 kg of CO_2 per kW.

Chapter 5 – Conclusion & Recommendations

Finally, the combined results are used to develop from the exergy analysis and greenhouse gas emissions analysis performed. Solar and wind resources depend entirely on the available natural resources, and as observed in the results, the wind and solar resources available to the community are low. Wind speeds in the community average from 8 km/h to 13 km/h while solar irradiance is low on average. Wind and solar result in emissions rates of 1084 kg CO_2/ kW and 861 kg CO_2/kW. Hydrogen can operate at an exergy efficiency of 19.4% while emitting 461 kg CO_2/kW, when fuel delivery is considered this increase to 5491 kg CO_2/kW, see Table 1.

Table 1 Cumulated Results

Energy Source	Exergy Efficiency	Emissions (CO_2/kW)
Wind Turbines	7% – 26%	1084 kg
Photovoltaic Panels	17.5% – 20.5%	861 kg
Hydrogen Fuel Cell	28%	461 kg
Hydrogen Fuel Cell (Electrolysis & Transportation)	19.4%	5941 kg

While only considering the raw material input, as discussed in the scope of the project, the implementation of a fuel cell power generation system would be recommended as it would operate at the highest efficiency and emit the lowest emissions from raw material. The lower worst-case efficiencies of the solar and wind energy production coupled with the low energy available to the community would require more turbines and solar panels to generate power for the community. This would likely result in greater land development and possibly require a large capital investment. From the emissions analysis it was determined that the fuel cell emits the greatest quantity of emissions per kW, with wind being second best, and solar emitting the least. However, based on the scope of the study, hydrogen is selected as an energy storage alternative of the excess and curtailed power within the Southern grid. The implementation of hydrogen fuel cells, at an optimal current level, would require construction of a hydrogen infrastructure since current infrastructure relies heavily on steam methane reforming which itself emits greenhouse gases. Thus, the construction of an electrolysis system is needed to allow for clean hydrogen generation and grid flexibility. The use of clean energy methods in conjunction with diesel generators will also increase the lifetime of pre – installed system, as some of the generators are nearing the end of their design lifetime. The lack of wind and solar implementation results from the low exergy efficiency and high greenhouse gas emissions, low exergy efficiency is due to the low – velocity wind flows measured over a course of years, this implies that if turbines were to be installed for power generation in the community a large number of turbines would need to be installed, resulting in higher capital costs and more land use. The installation of more turbines also would result in a greater emission of greenhouse gases due to a greater quantity needed and a greater quantity of emissions during production. Implementation of solar panels in the form of a larger array would require land space in the community, will also result in land consumption, but panels can also be placed on rooftops allowing for quick implementation into the community's grid. As mentioned in the introduction and literature review many communities have already implemented small scale solar projects and some are beginning construction projects to implements them, this analysis further that's development and also provides an incentive to consider the implementation of fuel cells. The installation of a PEMFC will likely occur in a singular enclosed building as the various components can be housed in a shipping container as a packaged unit and will thusly require much less land than the other energy conversion sources.

Allowing communities to switch from diesel generators to cleaner renewable energy technologies will allow for communities to be more self-sufficient as they are able to better use resources available to them. Clean energy application could reduce the emissions of upwards of 8.9 million kgs of CO_2 due to diesel consumption from the Sandy Lake community per year, based on 2016 diesel consumption rate. The use of hydrogen would also benefit the southern gird by allowing for greater grid flexibility, especially as renewables are becoming cheaper and individual customers are adopting solar technologies and the greater adoption of electrical vehicles, the inconsistency of electrical demand will require grid flexibility in the future. The goals laid out in the Pan – Canadian Framework will be met through the implementation of renewable energy technologies throughout Canadian remote communities and reduce the community's greenhouse gas emissions and better their quality of life. Overall, the adoption of green energy in remote communities will benefit individuals, communities, Canada as a nation and the world as a whole.

Chapter 6 – Future Work

To properly implement a RE solution for communities it is important to consider a holistic method of assessment, the exergy assessment, and life cycle assessment, while a good start for community analysis, are not the only method of assessment that should be performed. Future work would explore the impact of the application of renewable energy production methods on the CO_2 output of the community, it is also important to determine the cost of energy to consumers as that is a major problem being faced currently, finally, it is important to consider the financial feasibility of such a project. The financial impact of the project on the residents of a community should also be considered. A project which cannot pay back its capital investments during the lifetime of the components is not a project that will be considered for application by stakeholders. A larger analysis can be developed and applied to various remote communities to develop a clean energy power plant.

Further analysis can be performed in better understanding the implementations of the adoption of RE technologies to produce electricity, by considered the end of life needs of the technologies. The various components of fuel cells, solar panels, and wind turbines also should be considered for LCA. Furthermore, for the purpose of this analysis, the values for the LCA were obtained from literature, instead, the values could be obtained from manufacturers and this would result in much more accurate results and this method can be used to determine the specific model for implementation.

Installation of RE technologies can also be explored as an addition to the, as during installation and construction processes there are emissions due to the use of heavy construction equipment. The maintenance regimes set out by manufacturers and the materials needed for maintenance should also be considered for the purpose of the LCA, for example, wind turbines require various oils and fluids to maintain gearbox health. Data provided by manufacturers during the manufacturing process would allow for the assessment to increase its accuracy.

Furthermore, the solar and wind resources are also best measured firsthand at the location of the community, and proper surveying of the community layout can also be done. Another objective that may be explored for the blend development can be through capital cost analysis, along with exergy efficiency and greenhouse gas emissions, cost of construction is important to consider. For utilities, this may be the most important factor to consider keeping costs low in construction and thus lower costs to the customers. Finally, due to a diverse energy system a grid controller will be required to actively manage all the energy sources being fed into the grids. The implementation of a microgrid system can help manage all the generation sources, such as during times of high solar availability the system can produce energy from the sun and limit the consumption of hydrogen. Further work can be performed in the development of an optimal hydrogen generation method, though electrolysis is suggested, there are various other methods which can be considered.

Thermochemical cycles such as the Copper Chlorine thermochemical cycle [34], can make hydrogen – based energy production a more feasible form of hydrogen production and can work with other greenhouse gas emitters and reduce Ontario's total greenhouse gas emission.

REFERENCES

[1] M. Granovskii, I. Dincer, and M. A. Rosen, "Greenhouse gas emissions reduction by use of wind and solar energies for hydrogen and electricity production: Economic factors," *Int. J. Hydrogen Energy*, vol. 32, no. 8, pp. 927–931, 2007.

[2] A. Berger and C. Tricot, "The Greenhouse Effect," *Surv. Geophys.*, vol. 13, no. May, pp. 523–549, 1992.

[3] K. Karanasios and P. Parker, "Recent Developments in Renewable Energy in Remote Aboriginal Communities, Ontario, Canada," *Pap. Can. Econ. Dev.*, vol. 16, pp. 82–97, 2008.

[4] R. H. Crawford, "Life cycle energy and greenhouse emissions analysis of wind turbines and the effect of size on energy yield," *Renew. Sustain. Energy Rev.*, vol. 13, no. 9, pp. 2653–2660, 2009.

[5] C. Rosenzweig, A. Iglesius, X. B. Yang, P. . Epstein, and E. Chivian, "Climate change and extreme weather events - Implications for food production, plant diseases, and pests," *Glob. Chang. Hum. Heal. Heal.*, vol. 2, no. 2, pp. 90–104, 2001.

[6] B. Mitchell, John F., "The 'Greenhouse' effect and climate change," *Rev. Geophys.*, vol. 27, no. 1, pp. 115–139, 1989.

[7] S. S. Myers *et al.*, "Climate Change and Global Food Systems: Potential Impacts on Food Security and Undernutrition," *Ssrn*, no. February, pp. 259–278, 2017.

[8] J. Gale, "Overview of CO2 emissions sources, potential, transport and geographical distribution of storage possibilities," in *Proceedings of the workshop on CO2 dioxide capture and storage*, 2002, no. November, pp. 18–21.

[9] Environmental Protection Agency, "Global Greenhouse Gas Emissions Data | Greenhouse Gas (GHG) Emissions | US EPA." [Online]. Available: https://www.epa.gov/ghgemissions/global-greenhouse-gas-emissions-data. [Accessed: 30-Sep-2019].

[10] Environment and Climate Change Canada, "Federal Actions for a Clean Growth Economy: Delivering on the Pan-Canadian Framework on Clean Growth and Climate Change," Gatineau, Qubec, 2016.

[11] E. and C. C. Canada, "Pan - Canadian Framework on Clean Growth and Climate Change," Gatineau, Qubec, 2016.

[12] M. Arriaga, C. A. Canizares, and M. Kazerani, "Renewable energy alternatives for remote communities in Northern Ontario, Canada," *IEEE Trans. Sustain. Energy*, vol. 4, no. 3, pp. 661–670, 2013.

[13] M. Arriaga, E. Nasr, and H. Rutherford, “Renewable Energy Microgrids in Northern Remote Communities,” *IEEE Potentials*, pp. 22–29, Sep-2017.

[14] M. Arriaga, C. A. Cañizares, and M. Kazerani, “Northern Lights: Access to Electricity in Canada’s Northern and Remote Communities,” *IEEE Power Energy Mag.*, vol. 12, no. 4, pp. 50–59, 2014.

[15] Environment and Climate Change Canada, “Canadian Environmental Sustainability Indicators: Greenhouse Gas Emissions,” *Environ. Clim. Chang. Canada*, 2019.

[16] G. O. Canada, “Status of Remote/Off Grid Communities in Canada,” 2011.

[17] H. One, “Hydro One Remote Communities Inc , Distribution System Plan,” 2018.

[18] Natural Resources Canada, “The Atlas of Canada - Remote Communities Energy Database,” 2018. [Online]. Available: https://atlas.gc.ca/rced-bdece/en/index.html. [Accessed: 16-Oct-2019].

[19] CBC, “Explosions rocked plane after fire broke out: witness | CBC News,” *CBC News*, 2012. [Online]. Available: https://www.cbc.ca/news/canada/thunder-bay/explosions-rocked-plane-after-fire-broke-out-witness-1.1265058. [Accessed: 24-Aug-2019].

[20] IESO, “Ontario’s Electricity System,” *2019*. [Online]. Available: http://www.ieso.ca/localContent/ontarioenergymap/index.html. [Accessed: 24-Aug-2019].

[21] O. E. B. Government of Canada, National Energy Board, “NEB - Provincial and Territorial Energy Profiles - Ontario.” [Online]. Available: https://www.neb-one.gc.ca/nrg/ntgrtd/mrkt/nrgsstmprfls/on-eng.html. [Accessed: 03-Jul-2019].

[22] Independent Electricity System Operator, “Power Data,” 2019. [Online]. Available: http://www.ieso.ca/power-data. [Accessed: 18-Aug-2019].

[23] G. Zochodne, “Sell surplus electricity at a discount to Ontario businesses, rather than exporting at loss, province urged,” *Financial Post*, 2017.

[24] M. McPherson and S. Tahseen, “Deploying storage assets to facilitate variable renewable energy integration: The impacts of grid flexibility, renewable penetration, and market structure,” *Energy*, vol. 145, pp. 856–870, 2018.

[25] H. Blanco and A. Faaij, “A review at the role of storage in energy systems with a focus on Power to Gas and long-term storage,” *Renew. Sustain. Energy Rev.*, vol. 81, no. May 2017, pp. 1049–1086, 2018.

[26] M. Jentsch, T. Trost, and M. Sterner, “Optimal use of Power-to-Gas

energy storage systems in an 85% renewable energy scenario," *Energy Procedia*, vol. 46, pp. 254–261, 2014.

[27] H. Ibrahim, A. Ilinca, and J. Perron, "Energy storage systems-Characteristics and comparisons," *Renew. Sustain. Energy Rev.*, vol. 12, no. 5, pp. 1221–1250, 2008.

[28] A. J. Pimm, S. D. Garvey, and M. de Jong, "Design and testing of Energy Bags for underwater compressed air energy storage," *Energy*, vol. 66, pp. 496–508, 2014.

[29] Z. Long and Q. Zhiping, "Review of Flywheel Energy Storage System," *Proc. ISES World Congr. 2007 (Vol. I – Vol. V)*, pp. 2815–2819, 2009.

[30] I. Kougias and S. Szabó, "Pumped hydroelectric storage utilization assessment: Forerunner of renewable energy integration or Trojan horse?," *Energy*, vol. 140, pp. 318–329, 2017.

[31] H. D. Abruña, Y. Kiya, and J. C. Henderson, "Batteries and electrochemical capacitors," *Phys. Today*, vol. 61, no. 12, pp. 43–47, 2008.

[32] I. Dincer and C. Acar, "ScienceDirect Review and evaluation of hydrogen production methods for better sustainability," *Int. J. Hydrogen Energy*, vol. 40, no. 34, pp. 11094–11111, 2015.

[33] R. Kothari, D. Buddhi, and R. L. Sawhney, "Comparison of Environmental and Economic Aspects of Various Hydrogen Production Methods," *Renew. Sustain. Energy Rev.*, vol. 12, no. 2, pp. 553–563, 2008.

[34] G. F. Naterer *et al.*, "Progress in thermochemical hydrogen production with the copper–chlorine cycle," *Int. J. Hydrogen Energy*, vol. 40, 2015.

[35] Frederick J. Barclay, *Fuel Cells , Engines and An Exergy Approach*. 2006.

[36] R. O'Hayre, S. W. Cha, W. Colella, and F. B. Prinz, *Fuel cell fundamentals*, Third. Hoboken, New Jersey: John Wiler & Sons, 2009.

[37] J. Andersson and S. Grönkvist, "Large-scale storage of hydrogen," *Int. J. Hydrogen Energy*, vol. 44, no. 23, pp. 11901–11919, 2019.

[38] L. Schlapbach and A. Züttel, "for Mobile Applications," *Nature*, pp. 353–358, 2001.

[39] J. F. Manwell, J. G. McGowan, and A. L. Rogers, *Wind energy explained: theory, design and application*. 2009.

[40] T. Renzo, "Sources of wind turbine noise and sound propagation," *Acoust. Aust.*, vol. 40, no. 1, pp. 20–27, 2012.

[41] O. A. Jianu and M. A. Rosen, "Preliminary Assessment of Noise Pollution Prevention in Wind Turbines Based on an Exergy Approach," *Eur. J. Sustain. Dev. Res.*, vol. 1, no. 2, pp. 1–9, 2017.

[42] M. Nijhawan and O. A. Jianu, "Investigation of Noise Generation of a Two Dimension NACA 0006 Airfoil at Varying Flow Velocities," *Int. J. Green Energy*, pp. 1–17.

[43] W. Wang and O. A. Jianu, "A smart sensing unit for vibration measurement and monitoring," *IEEE/ASME Trans. Mechatronics*, vol. 15, no. 1, pp. 70–78, 2010.

[44] S. E. Ambrose, R. W. Rand, C. M. E. Krogh, and J. Jakobsen, "Infrasound Emission from Wind Turbines," *J. Low Freq. Noise Vib. Act. Control*, vol. 24, no. 3, pp. 145–155, 2005.

[45] H. Klug, "Noise From Wind Turbines Standards and Noise Reduction Procedures," *Forum Acusticum*, no. September, pp. 16–20, 2002.

[46] R. Tonin, "Sources of wind turbine noise and sound propagation," *Acoust. Aust.*, vol. 40, no. 1, pp. 20–27, 2012.

[47] K. Bolin, "Wind Turbine Noise and Natural Sounds- Masking , Propagation and Modeling," 2009.

[48] M. Gul, Y. Kotak, and T. Muneer, "Review on recent trend of solar photovoltaic technology," *Energy Explor. Exploit.*, vol. 34, no. 4, pp. 485–526, 2016.

[49] B. Sreewirote, A. Noppakant, and C. Pothisarn, "Increasing efficiency of an electricity production system from solar energy with a method of reducing solar panel temperature," in *2017 International Conference on Applied System Innovation (ICASI)*, 2017, pp. 1308–1311.

[50] M. Arriaga, C. A. Cañizares, and M. Kazerani, "Long-term renewable energy planning model for remote communities," *IEEE Trans. Sustain. Energy*, vol. 7, no. 1, pp. 221–231, 2016.

[51] J. Knowles, "Power shift: Electricity for Canada's remote communities," no. September, p. 65, 2016.

[52] K. Karanasios and P. Parker, "Recent Developments in Renewable Energy in Remote Aboriginal Communities, Newfoundland and Labrador, Canada," *Pap. Can. Econ. Dev.*, vol. 16, pp. 109–118, 2016.

[53] D. Gielen, F. Boshell, D. Saygin, M. D. Bazilian, N. Wagner, and R. Gorini, "The role of renewable energy in the global energy transformation," *Energy Strateg. Rev.*, vol. 24, no. January, pp. 38–50, 2019.

[54] J. Mohtasham, "Review Article-Renewable Energies," *Energy Procedia*, vol. 74, pp. 1289–1297, 2015.

[55] N. S. Lewis, "Toward Cost-Effective Solar Energy Use," no. February, pp. 798–802, 2007.

[56] C. K. Woo and J. Zarnikau, "Renewable energy's vanishing premium in

Texas's retail electricity pricing plans," *Energy Policy*, vol. 132, no. January, pp. 764–770, 2019.

[57] J. I. Peña and R. Rodríguez, "Are EU's Climate and Energy Package 20-20-20 targets achievable and compatible? Evidence from the impact of renewables on electricity prices," *Energy*, vol. 183, pp. 477–486, 2019.

[58] M. I. Blanco, "The economics of wind energy," *Renew. Sustain. Energy Rev.*, vol. 13, no. 6–7, pp. 1372–1382, 2009.

[59] O. Le Corre, J. S. Broc, and I. Dincer, "Energetic and exergetic assessment of solar and wind potentials in Europe," *Int. J. Exergy*, vol. 13, no. 2, p. 175, 2013.

[60] A. Ahmadi and M. A. Ehyaei, "Exergy Analysis and Optimisation of a Wind Wurbine Using Genetic and Searching Algorithms," *Int. J. Exergy*, vol. 6, no. 4, pp. 457–476, 2009.

[61] I. Dincer and M. A. Rosen, "Chapter 1 - Thermodynamic Fundamentals," in *Exergy*, I. Dincer and M. A. Rosen, Eds. Amsterdam: Elsevier, 2007, pp. 1–22.

[62] R. Cownden, M. Nahon, and M. A. Rosen, "Exergy analysis of a fuel cell power system for transportation applications," *Exergy, An Int. J.*, vol. 1, no. 2, pp. 112–121, 2001.

[63] M. L. Kubik, P. J. Coker, and C. Hunt, "Using Meteorological Wind Data to Estimate Turbine Generation Output: A Sensitivity Analysis," *Proc. World Renew. Energy Congr. – Sweden, 8–13 May, 2011, Linköping, Sweden*, vol. 57, pp. 4074–4081, 2011.

[64] A. D. Şahin, I. Dincer, and M. A. Rosen, "Thermodynamic analysis of wind energy," *Int. J. Energy Res.*, vol. 30, no. 8, pp. 553–566, 2006.

[65] M. Nijhawan and O. A. Jianu, "Investigation of Sustainable Energy Alternatives for Powering Remote Communities in Northern Ontario Investigation of Sustainable Energy Alternatives for Powering Remote Communities in Northern Ontario," *Int. J. Green Energy*, 2019.

[66] Environment Canada, "Historical Data - Climate - Environment and Climate Change Canada 2008-2018," *Government of Canada*, 2018. [Online]. Available: http://climate.weather.gc.ca/historical_data/search_historic_data_stations_e.html?searchType=stnName&timeframe=1&txtStationName=Sandy+Lake&searchMethod=contains&optLimit=yearRange&StartYear=1840&EndYear=2019&Year=2019&Month=8&Day=13&selRowPerPage=25. [Accessed: 13-Aug-2019].

[67] F. Fouladi, P. Henshaw, and D. S. K. Ting, "Enhancing Smart Grid realisation with accurate prediction of photovoltaic performance based on weather forecast," *Int. J. Environ. Stud.*, vol. 70, no. 5, pp. 754–764,

2013.

[68] C. Solar Inc, “KuMax (1000 V / 1500 V) SUPER HIGH EFFICIENCY POLY GEN4 MODULE CS3U-345|350|355|360P,” pp. 2016–2017, 2000.

[69] H. Efficiency and P. Module, “High efficiency poly module cs3u-350|355|360|365p-fg,” no. 1, 2015.

[70] European Commision, “JRC Photovoltaic Geographical Information System (PVGIS) - European Commission,” 2017. [Online]. Available: https://re.jrc.ec.europa.eu/pvg_tools/en/tools.html#PVP. [Accessed: 13-Aug-2019].

[71] A. Rabbani and M. Rokni, “Dynamic Characteristics of an Automotive Fuel Cell System for Transitory Load Changes,” *Sustain. Energy Technol. Assessments*, vol. 1, no. 1, pp. 34–43, 2013.

[72] a Yilanci, H. K. Ozturk, O. Atalay, and I. Dincer, “Exergy Analysis of a 1.2 kWp PEM Fuel Cell System,” *Proc. 3rd Int. Energy, Exergy Environ. Symp.*, no. February, pp. 1–10, 2007.

[73] ISO, “Environmental management - Life Cycle Assessment - Principles and Framework,” *Int. Organ. Stand.*, vol. 3, p. 20, 2006.

[74] C. Ghenai, “Life Cycle Analysis of Wind Turbine,” *Sustain. Dev. - Energy, Eng. Technol. - Manuf. Environ.*, 2012.

[75] T. E. Graedel and B. R. Allenby, *Industrial Ecological and Sustainable Engineering*. Upper Sabble River: Pearson, 2010.

[76] D. Nugent and B. K. Sovacool, “Assessing the lifecycle greenhouse gas emissions from solar PV and wind energy: A critical meta-survey,” *Energy Policy*, vol. 65, pp. 229–244, 2014.

[77] M. R. Kabir, B. Rooke, G. D. M. Dassanayake, and B. A. Fleck, “Comparative life cycle energy, emission, and economic analysis of 100 kW nameplate wind power generation,” *Renew. Energy*, vol. 37, no. 1, pp. 133–141, 2012.

[78] Natural Resources Canada, *Stand-Alone Wind Energy Systems: A Buyer’s Guide*. 2003.

[79] E. Hosseinzadeh and M. Rokni, “Development and validation of a simple analytical model of the proton exchange membrane fuel cell (PEMFC) in a fork-lift truck power system,” *Int. J. Green Energy*, vol. 10, no. 5, pp. 523–543, 2013.

[80] M. A. Rosen, “Energy and exergy analyses of electrolytic hydrogen production,” *Int. J. Hydrogen Energy*, vol. 20, no. 7, pp. 547–553, 1995.

[81] D. R. Wilburn, “Wind Energy in the United States and Materials Required for the Land-Based Wind Turbine Industry From 2010

Through 2030. U.S. Geological Survey Scientific Investigations Report 2011 – 5036," pp. 1–22, 2011.

[82] L. Xu, S. Zhang, M. Yang, W. Li, and J. Xu, "Environmental effects of China's solar photovoltaic industry during 2011–2016: A life cycle assessment approach," *J. Clean. Prod.*, vol. 170, no. September, pp. 310–329, 2018.

[83] M. S. R. Frischknecht, R. Itten, P. Sinha, M. de Wild-Scholten, J. Zhang, V. Fthenakis, H. C. Kim, M. Raugei, "Life Cycle Inventories and Life Cycle Assessment of Photovoltaic Systems," 2015.

[84] L. Xu, S. Zhang, M. Yang, W. Li, and J. Xu, "Environmental effects of China's solar photovoltaic industry during 2011–2016: A life cycle assessment approach," *J. Clean. Prod.*, vol. 170, no. September, pp. 310–329, 2018.

[85] N. A. Ludin *et al.*, "Prospects of life cycle assessment of renewable energy from solar photovoltaic technologies: A review," *Renew. Sustain. Energy Rev.*, vol. 96, no. April, pp. 11–28, 2018.

[86] L. Tschümperlin, P. Stolz, and R. Frischknecht, "Life cycle assessment of low pow- er solar inverters (2.5 to 20 kW) Swiss Federal Office of Energy SFOE," vol. 3, no. October, 2016.

[87] M. Pehnt, "Life-cycle assessment of fuel cell stacks," *Int. J. Hydrogen Energy*, vol. 26, no. 1, pp. 91–101, 2001.

[88] R. Gerboni, M. Pehnt, P. Viebahn, and E. Lavagno, "Deliverable n° 9.2 - RS 1a. Final report on technical data , costs and life," pp. 1–75, 2008.

[89] M. F. Ashby, *Materials and the Environment – Eco-Informed Material Choice*. 2013.

[90] M. Ashby, *Materials and the Environment: Eco-Informed Material Choice*. .

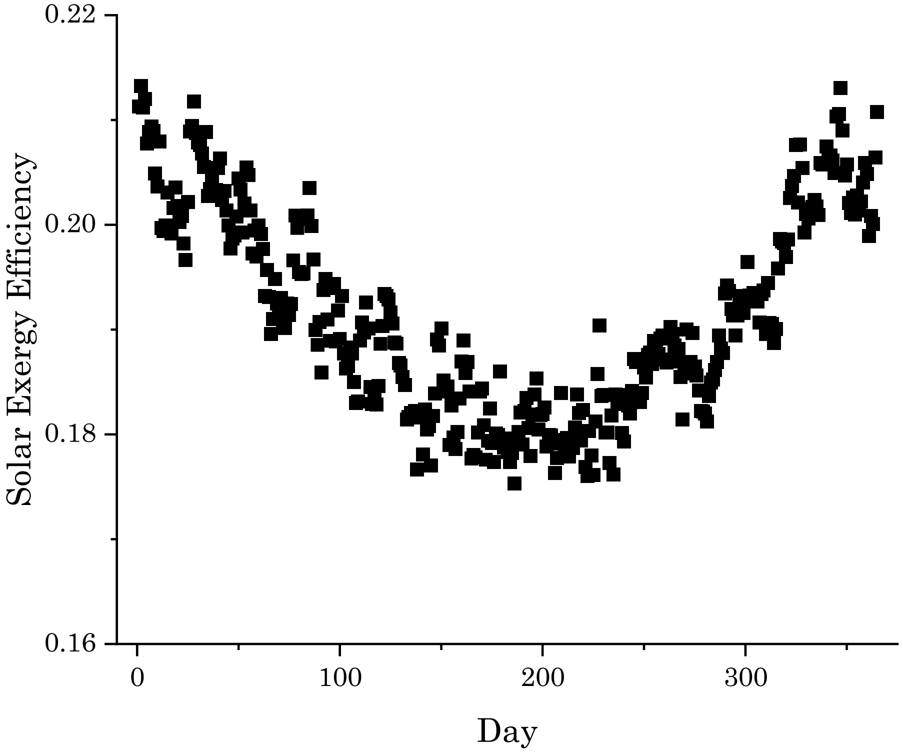
[91] Q. Dai, J. C. Kelly, L. Gaines, and M. Wang, "Life Cycle Analysis of Lithium-Ion Batteries for Automotive Applications," *Batteries*, vol. 5, no. 2, p. 48, 2019.

[92] J. Wu *et al.*, "A review of PEM fuel cell durability: Degradation mechanisms and mitigation strategies," *J. Power Sources*, vol. 184, no. 1, pp. 104–119, 2008.

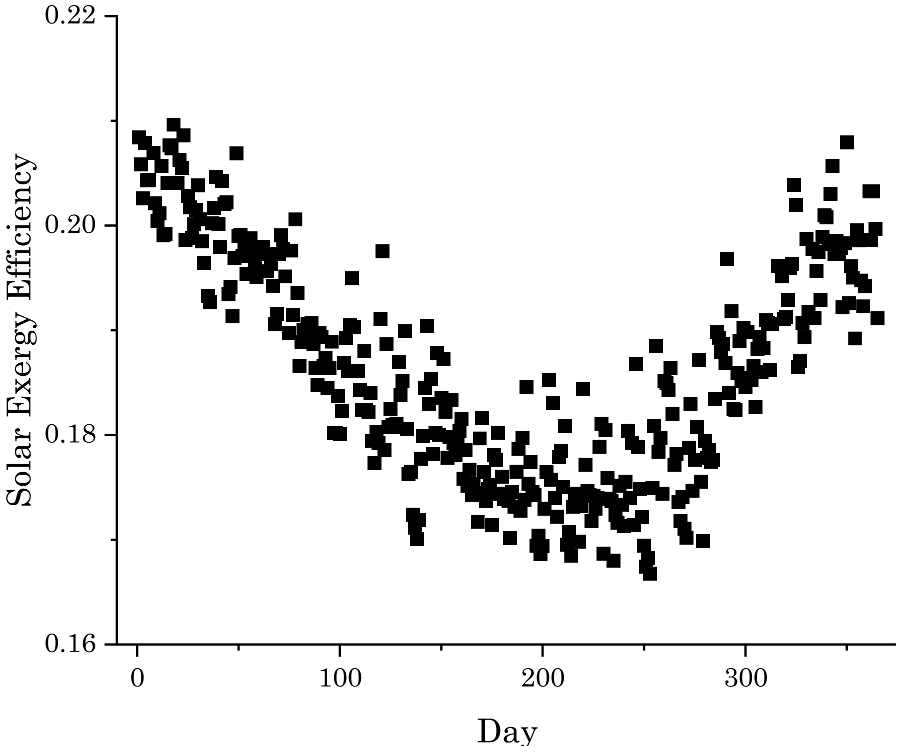
[93] Hydro One, "Hydro One Remote Communities Inc.: Greenhouse Gas Inventory and Action Plan," 2015.

[94] Linde Corporation, "Linde raises the bar for hydrogen transport efficiency | The Linde Group," 2013. [Online]. Available: https://www.the-lindegroup.com/en/news_and_media/press_releases/news_20130925.html. [Accessed: 25-Sep-2019].

APPENDICES



Appendix 1 Solar Exergy Efficiency 2010



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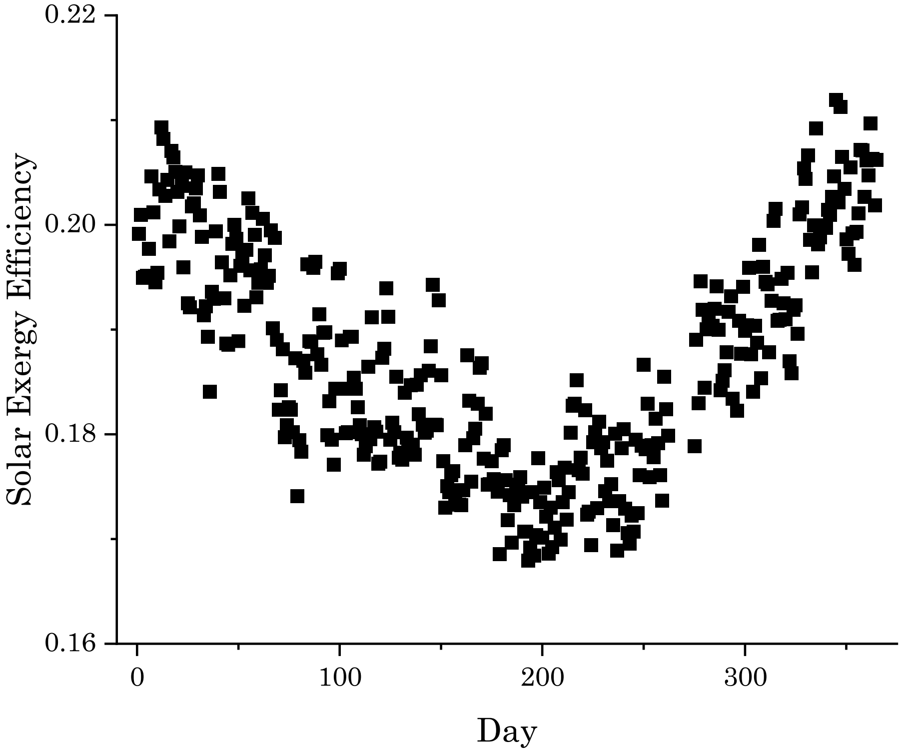

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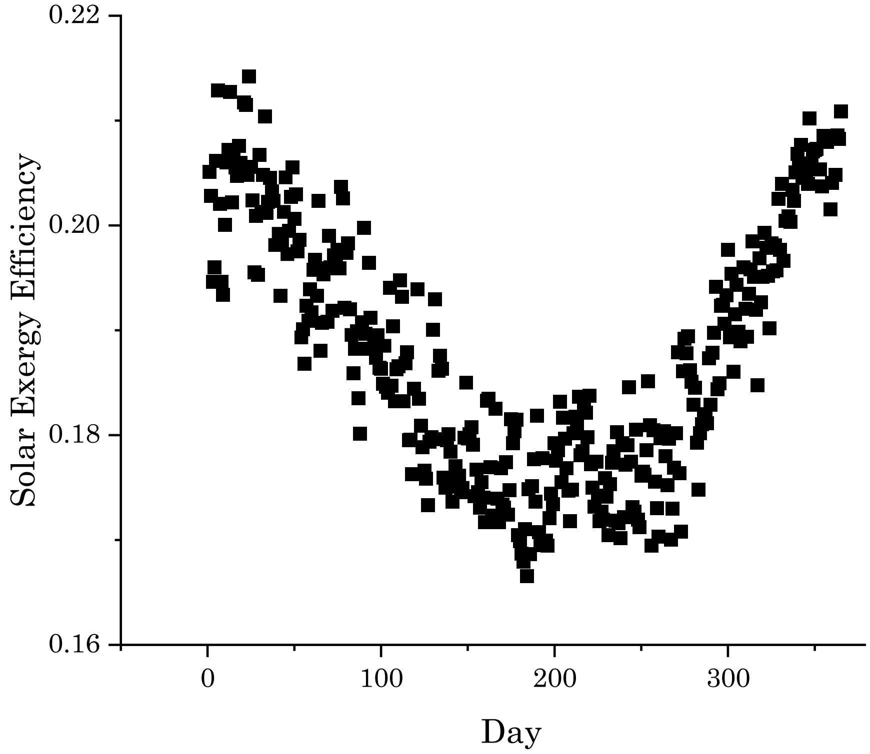

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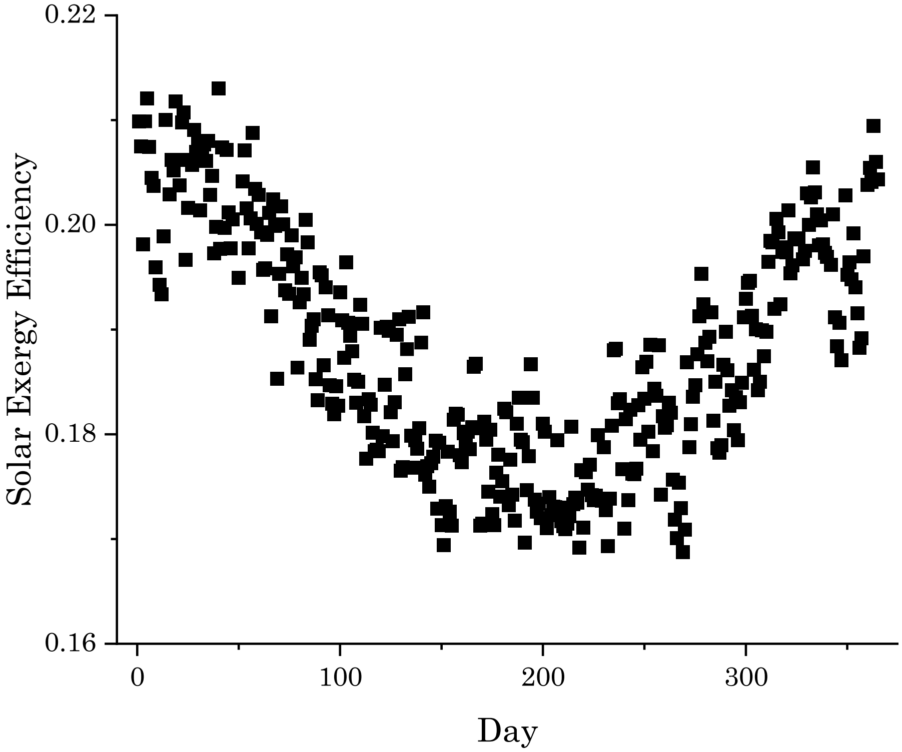

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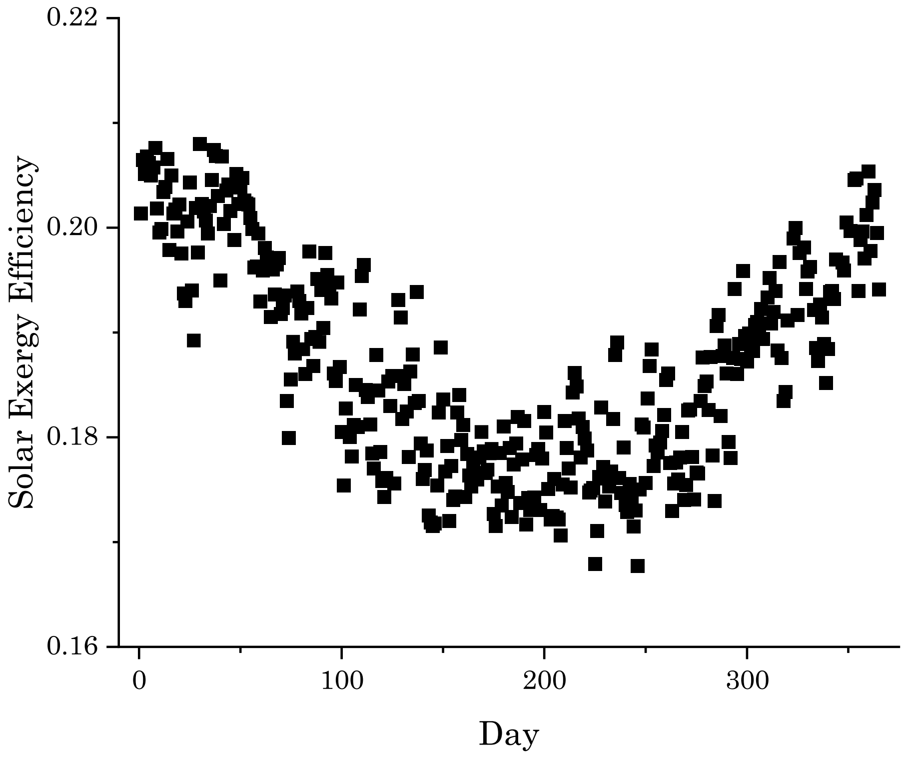

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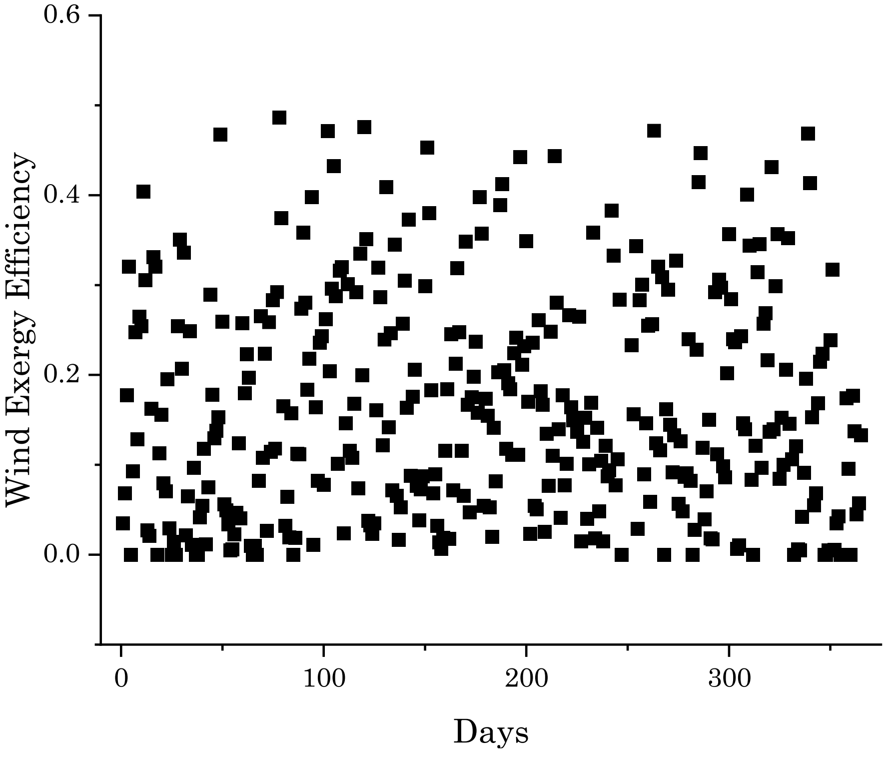

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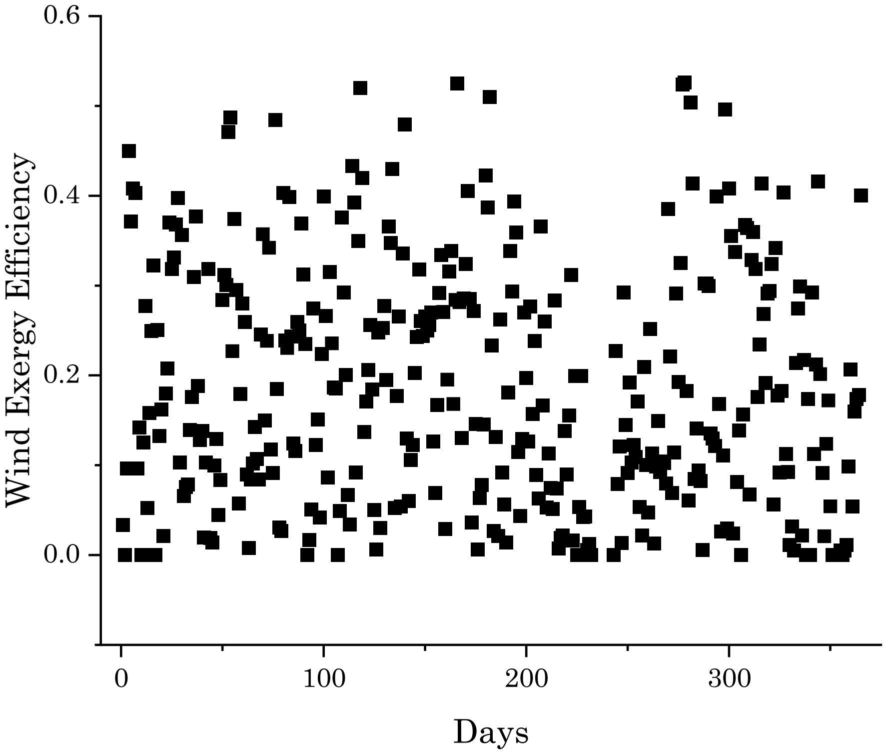

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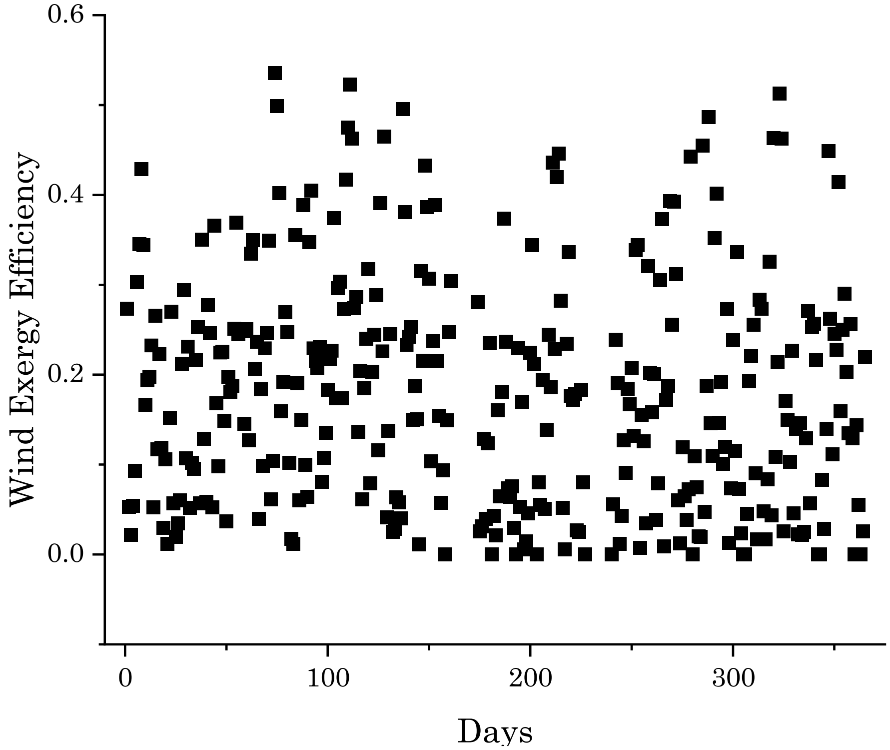

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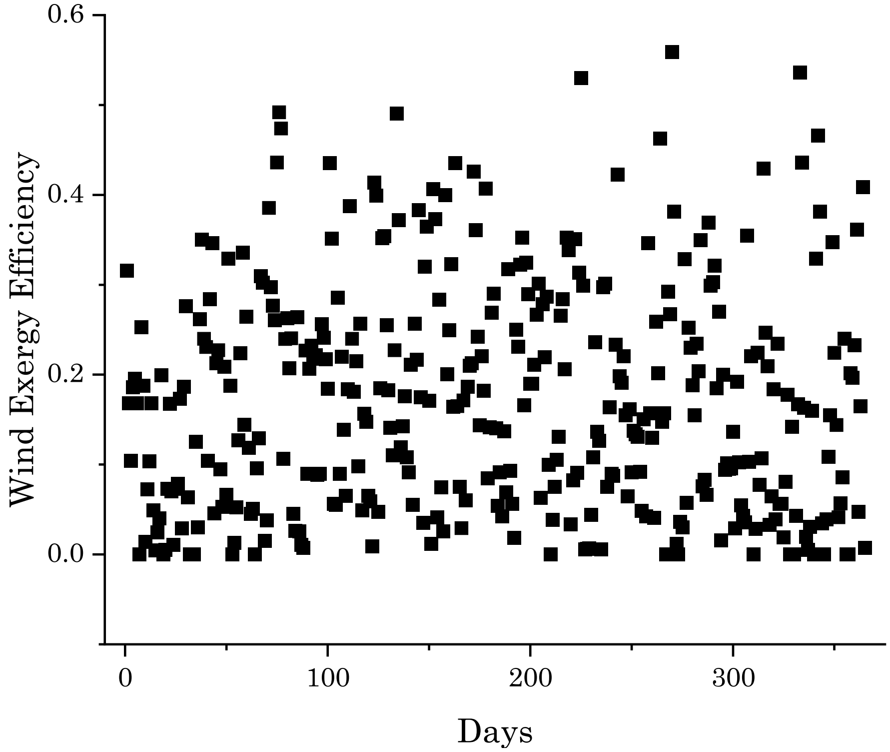

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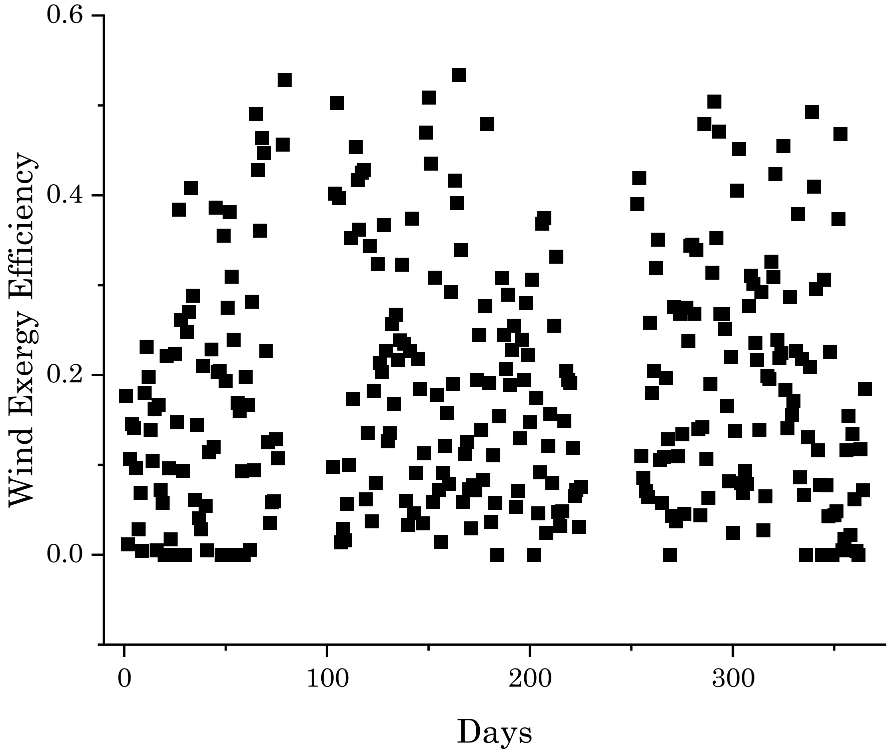

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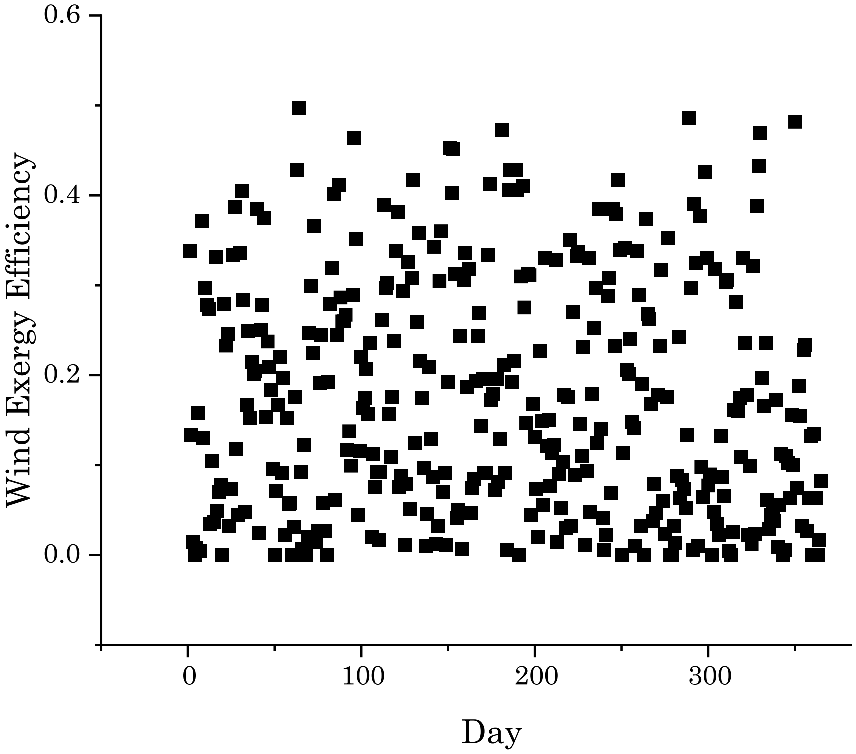

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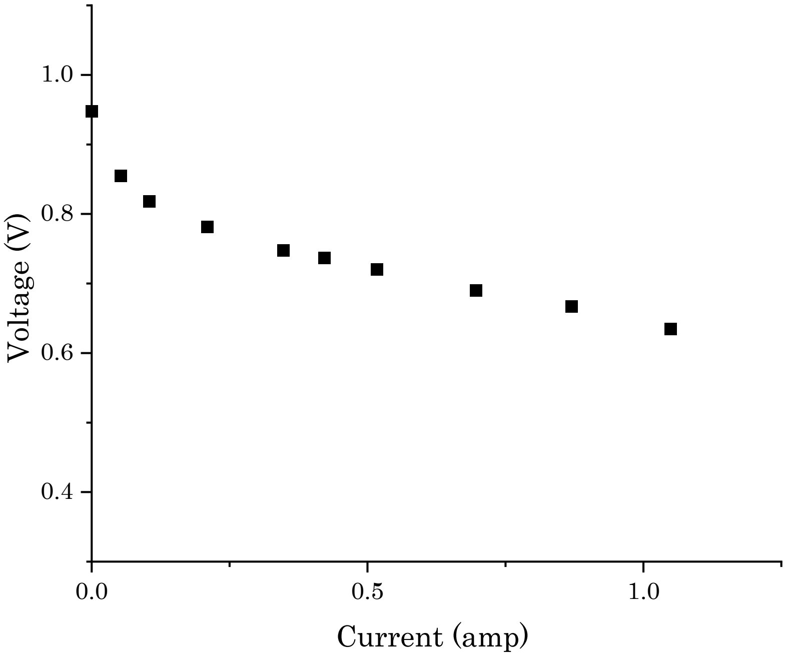

Appendix 13 Fuel Cell j-V Curve

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