Life cycle assessment of bioenergy production using wood pellets: The case of remote communities in Canada

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Abstract

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A reliable and environmentally friendly energy source is crucial to remote Canadian communities. Currently, fossil fuels are the primary source of electricity and heat in these communities. Diesel generators mostly powered these communities, contributing to climate change due to fuel transportation and emissions. Therefore, there is an urgent need to reduce fossil fuel reliance in these communities. We examined wood pellets' use in a remote Canadian community using Life Cycle Analysis (LCA). In addition, the combustion of wood pellets will be compared with diesel combustion. To perform the LCA, we utilized SimaPro (version 8.4.0.0), a widely used software for conducting LCA. SimaPro provides a comprehensive platform for modeling and analyzing the environmental performance of products or processes. The Ecoinvent 3 library also provided life cycle inventory (LCI) data for a variety of materials, processes, and energy systems. Pellets LCA covered harvesting, transportation, sawmill operation, pellet production, and combustion stages. Our first step was to collect data on these five stages. Furthermore, these stages were compared in eight impact categories (Global warming, carcinogenic, non-carcinogenic, ozone depletion, respiratory effects, smog, acidification, ecotoxicity, eutrophication, and fossil fuel depletion). According to the results, pelletization and combustion are the most harmful stages to the environment, especially non carcinogenics effects for the pelletization and respiratory effects of pellet combustion. Lastly, we compared wood pellet combustion with diesel combustion to assess bioenergy's efficiency. We found that the combustion of wood pellets performs better in many impact categories than in burning diesel, especially in non-carcinogenic ones.

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List of Abbreviations

BC	British Columbia
CO	Carbon Monoxide
EPD	Environmental Products Declaration
GHG	Greenhouse Gas
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
NO_x	Nitrogen Oxides
PM	Particulate Matter
PM_{10}	Particulate Matter Less Than or Equal to 10 µm
$PM_{2.5}$	Particulate Matter Less Than or Equal to 2.5 µm
PJ	Petajoules
SO_2	Sulfur Dioxide
TRACI	Tool For The Reduction And Assessment of Chemical and Other Environmental Impacts
VOCs	Volatile Organic Compounds
WPAC	Wood Pellet Association of Canada

Chapter 1: Introduction

1.1 General Overview

Greenhouse gas (GHG) emissions are contributing to global warming and climate change, affecting human and ecosystem health, as well as the security of food and water supplies (Cambero et al., 2015). Canada has committed to reducing its total GHG emissions by 40 to 45% until 2030 (based on 2005 emissions as the benchmark) and reaching a net zero by 2050 (Canada, 2022). Promoting renewable energy has emerged as a solution to offset GHG emissions (Cools, 2022). As can be seen in Figure 1, there was a total supply of 12,795 petajoules (PJ) of energy in Canada in 2019, of which over 75% came from fossil fuels. A total of 2,067 PJ of energy is generated by renewable sources, of which 566 PJ comes from bioenergy. Over the past few years, fossil fuel consumption - mainly natural gas - has increased in Canada, while renewable energy supply has remained relatively stable (between 16% and 18%) (Vanderfleet et al., 2021).

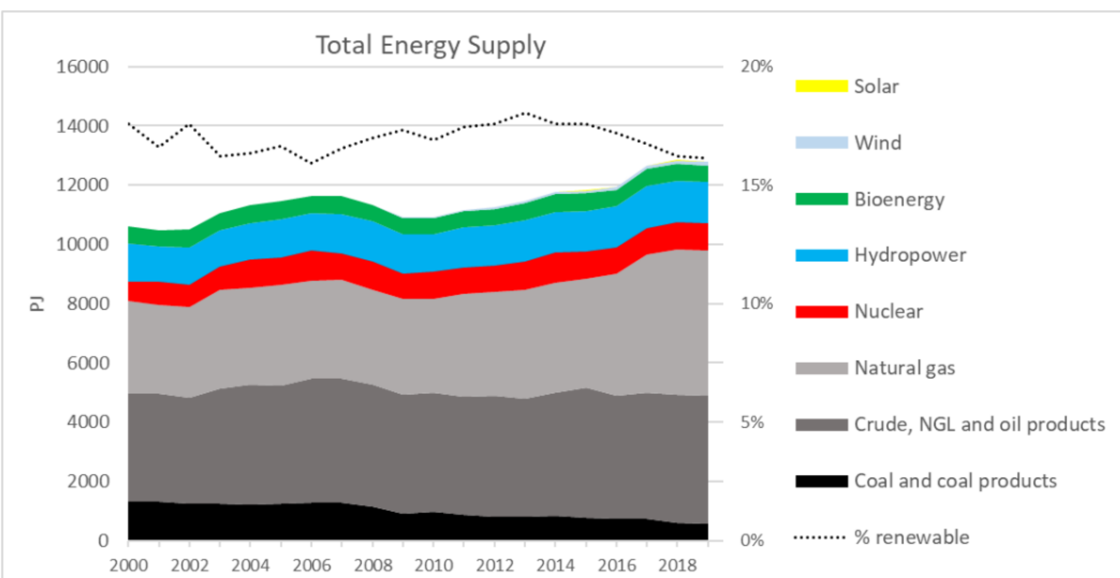

Figure 1 Canada's total energy supply and the contribution of different energy sources (Vanderfleet et al., 2021)

Canada is working towards its goal of generating 90% of its electricity from non-emitting sources by 2030 in collaboration with provinces and territories. The country is taking steps to minimize the environmental impact of electricity generation, both domestically and globally. To achieve this, Canada plans to phase out the use of traditional coal-fired electricity and implement new regulations to reduce emissions from natural gas-fired and diesel-fired electricity. The government is also promoting energy conservation and emission reduction through programs like the Low Carbon Economy Fund and Climate Action Incentive. Additionally, Canada is investing in smart grids to facilitate access to clean electricity from neighboring provinces and implementing a carbon pollution pricing system that will hold the electricity industry accountable for reducing emissions (Canada, 2019).

The extreme weather condition in remote communities of Canada makes energy supplies vital to survival of these regions as well as the quality of life of the residents. Due to the remoteness of these communities, they are not connected to main grids or supply channels of other energy carriers (ex. natural gas pipelines). This has forced many communities to rely on stand-alone off-grid energy facilities. Fossil fuels, particularly diesel, are the primary energy source for most of these isolated villages due to ease of transport and storage (Mafakheri et al., 2020). Fossil fuel dependence and such a lack of diversity in energy sources limits economic, environmental, and social development of these communities (Khoddami et al., 2021). In addition, this phenomenon has contributed to raising GHG emissions in these communities.

As a renewable energy source, biomass has several advantages, including compatibility with existing infrastructure and quick dispatch, which refers to its capability to be rapidly deployed and provide immediate energy supply when needed. In addition, using bioenergy instead of traditional fossil fuels has the potential to reduce GHG emissions and consumption of non-renewable resources (McKechnie et al., 2012). Biomass could be used as a backup fuel or replacement for diesel in northern regions due to its potential for carbon abatement. Similar to diesel, it could be transported to these remote destinations via existing logistical routes and arrangements for diesel (Mafakheri et al., 2020).

There is growing recognition that woody biomass can serve as a renewable energy feedstock. In addition to replacing non-renewable fossil fuels, it reduces GHG emissions, increases local and regional energy security, and could create new economic opportunities across its supply chain (Dias et al., 2017). Compressed wood fiber biofuels, known as wood pellets, have become popular for household heating (Laschi et al., 2016).

1.2 Research Gap and Significance

Despite Canada's abundant biomass production and capacity for timber exports, there is a lack of research on the environmental impacts of using wood pellets as an alternative fuel source, specifically in domestic settings in remote regions. While there is considerable emphasis on the export of Canadian wood pellets, research on their domestic use within Canada is lacking. Most existing studies have primarily examined the export market and the potential for international consumption of Canadian wood pellets. Given Canada's significant biomass resources and its role as a major timber exporter, it is essential to explore the opportunities and challenges associated with utilizing wood pellets within the country itself. This research gap becomes even more significant considering the rising demand for wood pellets as a primary feedstock in co-firing power plants in Europe and Southeast Asia. This highlights the need to assess the feasibility and benefits of domestic wood pellet utilization in Canada. Furthermore, the environmental and energy implications of long-distance pellet transportation, including the considerable energy consumption and associated environmental impacts, underscore the importance of investigating the potential advantages of using wood pellets locally as a sustainable energy source (Magelli et al., 2009).

Existing studies have primarily focused on comparing wood pellets to coal or natural gas, neglecting the unique context of remote communities in Canada that heavily rely on diesel for energy (Wang et al., 2017). It is crucial to understand the environmental implications of using wood pellets as a substitute for diesel in these regions to evaluate the potential benefits and challenges of transitioning to renewable energy sources.

Addressing these research gaps and investigating the use of wood pellets as a sustainable energy source in domestic and remote settings will contribute to a comprehensive understanding of their environmental impacts and the suitability of such a transition in remote Canadian communities.

1.3 Problem Statement

Remote communities in Canada depend heavily on diesel for their energy needs due to limited access to main grids or alternative energy carriers like natural gas. This reliance on diesel not only limits the economic, environmental, and social development of these communities but also contributes to increased GHG emissions (Khoddami et al., 2021). Reducing diesel consumption and transitioning to cleaner energy sources are essential to mitigate environmental impacts and improve the quality of life in these regions.

Considering the challenges faced by remote communities in Canada and the importance of reliable energy supplies in extreme weather, the potential benefits of transitioning from diesel to wood pellets as a renewable energy source become even more significant (Mafakheri et al., 2020). Biomass, particularly wood pellets, offers several advantages as a renewable energy source, including compatibility with existing infrastructure and the potential for carbon abatement (McKechnie et al., 2012).

The production of wood pellets on a local scale not only reduces dependence on fossil fuels but also fosters economic self-sufficiency, particularly in remote communities. This transition brings about a significant reduction in the environmental footprint while simultaneously bolstering energy security and fostering the principles of sustainable development. Embracing wood pellets enables these communities to pave the way for a more sustainable future, marked by reduced environmental impact and heightened resilience in their pursuit of sustainable growth. However, understanding the environmental implications and feasibility of using wood pellets in remote regions is crucial for effective decision-making.

1.4 Research Objectives

The primary objective of this research is to perform a comprehensive LCA of wood pellets in a remote community of Canada, considering the entire life cycle from harvesting to combustion. By analyzing various stages, including harvesting, transportation, sawmill operation, pelletization, and combustion, the environmental impacts of wood pellet utilisation will be assessed and compared to diesel. The LCA will encompass multiple impact categories, such as global warming, carcinogenic, non-carcinogenic, ozone depletion, respiratory effects, smog, acidification, ecotoxicity, eutrophication, and fossil fuel depletion.

The second objective of this study is to conduct a comparative analysis of the environmental performance between the combustion of wood pellets and the combustion of diesel. By quantifying and comparing the impacts of both fuel sources, this research aims to determine the extent to which wood pellets can serve as a cleaner alternative to diesel in terms of environmental sustainability. This comparison will provide valuable insights into the potential benefits and challenges associated with transitioning from diesel to wood pellets in remote communities of Canada.

1.5 Thesis Outline

In addition to the present chapter, this study comprises the following chapters:

Chapter 2 provides a comprehensive review of the literature relevant to the study. It explores advancements in reducing diesel usage in remote communities and discusses the potential of biomass, specifically wood pellets, as a replacement for fossil fuels. The chapter compares different types of woody biomasses, examines wood pellet's impact on air quality, and provides an overview of LCA) and its standards.

Chapter 3 describes the selected case study of Kwadacha First Nation, a remote community in British Columbia (BC). Chapter 4 presents the research methods employed, including the goal and scope of the study, system boundary definition, and data collection procedures. It also discusses the parameters considered for harvesting, sawmill operation, and pelletization.

Chapter 5 analyzes the results, focusing on each stage of the wood pellet production process and conducting a comparative analysis of stages and fuels. This chapter also provides a detailed discussion of the findings and interpreting the results within the research context.

Lastly, Chapter 6 presents the conclusions of the study, summarizing the key findings and their implications for the use of wood pellets as a sustainable energy source in remote communities, addressing limitations, and suggesting areas for future research.

Chapter 2: Literature Review

2.1 Chapter Overview

This chapter provides a comprehensive exploration of wood pellets as a renewable alternative to fossil fuels, focusing on their advancements, market trends, and environmental considerations. It begins by discussing the advancements made in reducing diesel usage in remote communities, highlighting the potential benefits of utilizing wood pellets in these areas.

Within the realm of biomass, wood pellets take center stage as a promising form of renewable energy. The chapter examines the process of manufacturing wood pellets, shedding light on the technology and steps involved in their production. It further investigates the Canadian wood pellet market, exploring its size, growth, and potential challenges. With a specific focus on BC, the chapter delves into the wood pellet industry in this region, analyzing the sourcing of wood pellet feedstock and the associated implications for sustainability.

The comparison between main woody biomasses is also examined, providing insights into their respective advantages and disadvantages. Additionally, the chapter emphasizes the importance of air quality when utilizing woody biomass as a fuel source, highlighting the potential impacts on air pollution, and discussing measures to mitigate such effects.

Lastly, the concept of LCA is introduced to evaluate the environmental impacts of wood pellets holistically. An overview of LCA and its standards is provided, encompassing the methodology used for assessing the life cycle impacts of wood pellets. The chapter concludes by discussing the product standards and guidelines within LCA, while also acknowledging the limitations of this methodology.

By offering a comprehensive exploration of wood pellets as a sustainable biomass fuel, this chapter sets the foundation for understanding their role in renewable energy systems and the associated considerations for their utilization.

2.2 Advancements in Reducing Diesel Usage in Remote Communities

In remote communities, diesel fuel is transported over long distances using trucks, ships, barges, or planes, since these communities are far from refineries. The fuel is stored in large above-ground tanks and delivered to customers by trucks. Diesel has advantages in such areas as it provides a reliable source of consistent heat and power in extreme climates. It is also easy to transport and can be stored for extended periods. However, there are disadvantages to diesel as well. It is expensive to purchase and transport, and its high cost is often subsidized to make it affordable for residents in remote communities. Diesel fuel emits carbon and particulates, leading to local air quality issues. There is also a risk of leaks or spills during storage and transportation, as well as from home tanks. Moreover, aging generators in these communities can fail when they are needed the most. Since these communities often rely on a single primary power source, a generator failure can result in a prolonged power outage (Government of Canada, 2023).

Between 2015 and 2020, renewable energy projects in remote areas of Canada experienced significant growth, nearly quadrupling in number (Lovekin et al, 2020). During this period, these areas saw a remarkable increase in solar capacity, with installations surpassing 11 times the capacity in 2015. Remote communities also achieved substantial diesel savings, saving over 12 million gallons through energy efficiency measures, renewable heat and power, and grid connections. However, despite these advancements, diesel consumption remains alarmingly high at 682 million liters per year in 2020, with two-thirds being used for heating and one-third for power. The transition to community energy systems utilizing renewable energy and zero-emission technologies presents promising opportunities for these communities to achieve energy security and economic benefits. Meeting the federal government's goal of eliminating diesel-powered electricity generation by 2030 and achieving net-zero carbon emissions by 2050 will require exploring different approaches and active participation from Indigenous community leaders. Additionally, it's important to note that while diesel is the primary fossil fuel used for energy and heating in remote areas, heavy fuel oil, natural gas, and propane also contribute and are collectively referred to as diesel equivalent or diesel eq for simplicity (Lovekin et al, 2020).

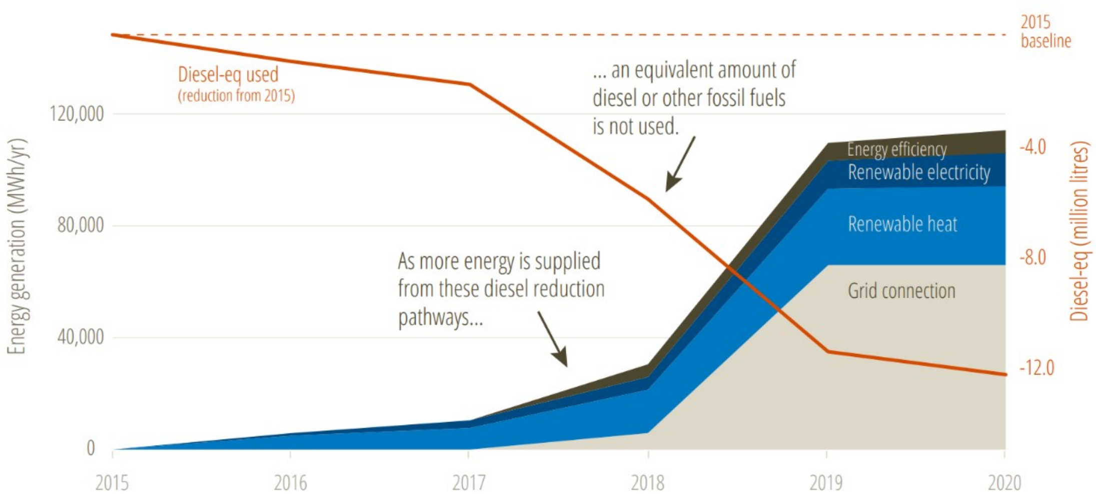

Figure 2 Approaches to decreasing diesel usage in remote communities (2015 to 2020) (Lovekin et al, 2020)

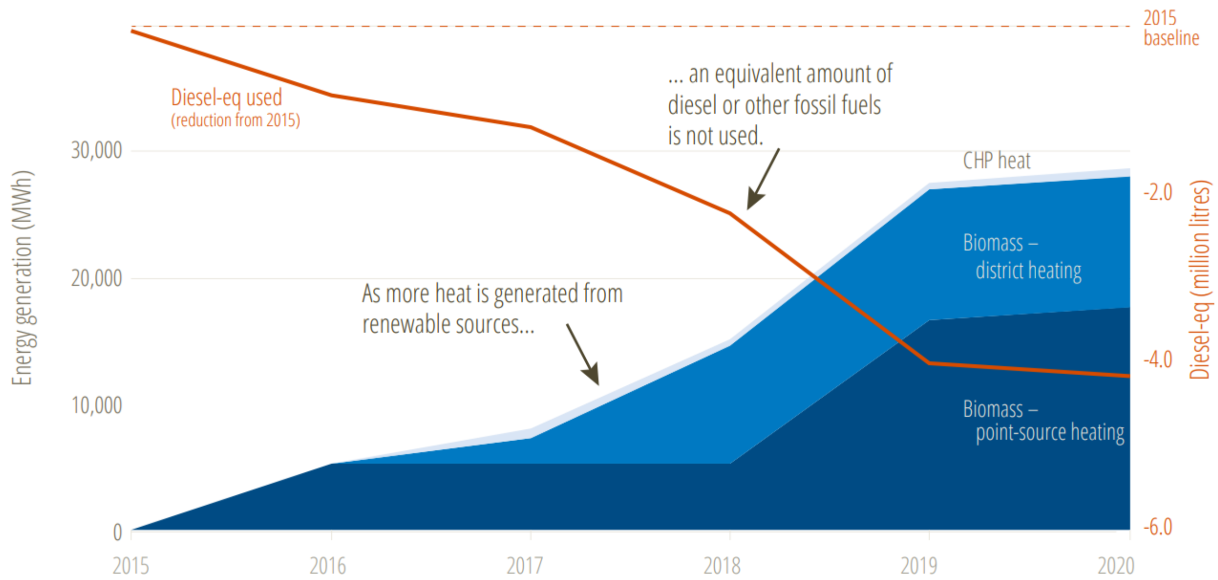

Figure 3 Growth of Renewable Heat Generation in Remote Communities (2015 to 2020) (Lovekin et al, 2020)

2.3 Biomass as a Fossil Fuel Replacement

As the devastating consequences of climate change become more apparent and expensive, the urgency to decarbonize will intensify. While wind and solar power, along with energy storage solutions, will undoubtedly play a critical role, they may not be enough to replace coal and natural gas thermal power for at least a decade. A viable solution to bridge this gap is to convert existing coal-fueled power plants to burn sustainably sourced fuels instead of coal. This approach has already been proven successful and implemented, and it will be an essential component in nations' efforts to decarbonize their power sectors. It will pave the way for a future dominated by renewable energy sources such as wind and solar, supported by massive energy storage systems (Cools, 2022).

Biomass has been used as a source of energy since the earliest days of human civilization. The first form of biomass as an energy source is the use of fire, which generates heat and is used for cooking. As a combustible carbon source, biomass is one of the simplest renewable energy sources on earth. Although biomass has historically been converted to energy primarily by combustion, it remains an essential energy source, particularly in developing countries that lack the bioenergy generating systems found in more developed nations. Thus, energy from biomass is not a recent discovery, but rather an age-old technique still used today to meet energy needs. (Seidel, 2021)

Plants and animals are the primary sources of biomass, organic material used for energy. Common biomass feedstocks include plants, wood, and waste. There are direct and indirect methods to convert the energy from these organisms into usable energy, including burning biomass to generate heat or electricity, and processing biomass to produce biofuels (National Geographic, 2022). In Canada, by-products of the forestry industry and municipal waste are the main sources of biomass. Bioenergy can be produced from trees unsuitable for lumber, thinning of stands, harvest residues, and even trees destroyed by fire, disease, or insects. Industrial by-products like wood residues and pulp residues are also potential sources of bioenergy (nrcan, 2020).

Figure 4 Types of Biomasses for Energy (Stein, 2023)

Biomass and biofuels have become increasingly popular as alternative fuel sources to fossil fuels in recent years. Unlike fossil fuels, which are finite and contribute to climate change by releasing GHGs like carbon dioxide when burned, biomass is a renewable and carbon-neutral energy source. This means that the plants that generate biomass capture nearly the same amount of carbon dioxide from the atmosphere as they release when burned, making them a sustainable and environmentally friendly option (U.S. Energy Information Administration, 2021).

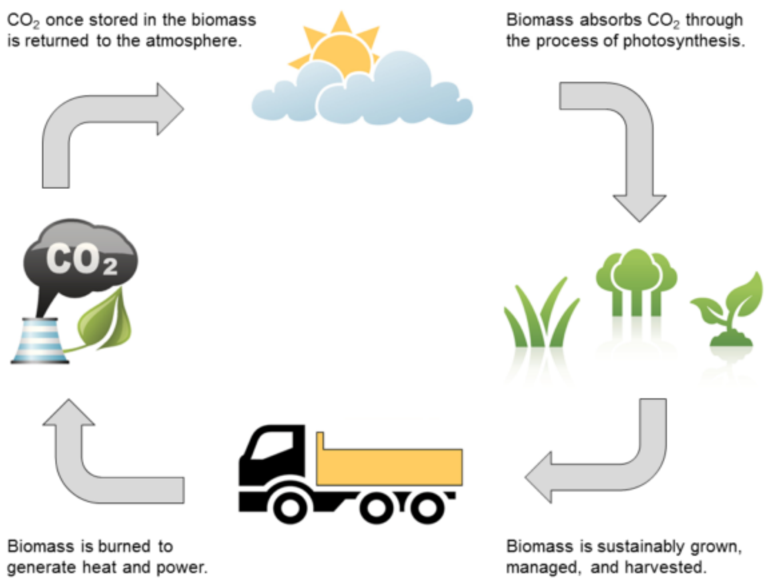

Figure 5 Carbon-Neutral Biomass Cycle (VIASPACE, 2023)

2.3.1 Wood Pellets as Biomass

Wood pellets are a sustainable and versatile form of biomass fuel, created by compressing a range of raw materials, including wood chips, sawdust, bark, brush, and agricultural waste like corn stalks and straw (naturallywood, 2021). Many pellet manufacturers use leftovers from other industrial operations or softwoods that are unsuitable for building materials to produce pellets (Roberts, 2021). This process of compressing wood residues under high pressure creates a refined and densified product that is uniform in size, shape, and density, making it ideal for use in pellet stoves and boilers (Indeck Energy Services, 2023).

One of the significant advantages of wood pellets is their high energy density, which is higher than that of other woody products, such as wood chips or logs. This high energy density makes them easier to store, transport, and use for energy production (Indeck Energy Services, 2023). Additionally, wood pellets have a consistent size and moisture content, which allows for more efficient combustion and reduced emissions compared to other forms of biomass (Roberts, 2021). The conversion of waste wood into low-carbon biofuel by the wood pellet industry not only helps to reduce waste but also emissions (naturallywood, 2021).

Figure 6 Wood Pellet (Harmanstoves, 2023)

2.3.1.1 The Process of Making Wood Pellets

The process of producing compressed wood pellets comprises nine distinct steps. Initially, wood fiber is delivered to the factory, including low-quality logs, wood chips made from crop residues, sawdust, and other wood manufacturing by-products. Roundwood is transported to the woodyard for processing, while wood chips and sawdust are conveyed directly to the woodchip pile. Bark is moved to a separate area, where it fuels the woodchip dryer.

Next, the Roundwood in the woodyard is debarked through a spinning drum, and the conveyor belt transports the bark to a storage facility for use as fuel. Afterward, the debarked logs are chipped into small, even pieces by rotating blades at the end of the drum debarker. The chips are screened for quality to remove any undesired materials such as sand, bark, or stones.

The wood chips are then sent to an industrial dryer, where they are subjected to a stream of super-heated air generated by the drum debarker's bark to reduce the moisture levels in the chips from 50% to around 12%. This ensures the quality and energy content in the final pellets. Subsequently, the dried chips are shredded into a fine fiber by hammer mills.

The wood fiber is then pushed into the pellet mill, where a revolving arm drives it through a metal die with several uniformly tiny holes. The extreme pressure heats up the wood fiber and bonds it together as it travels through the die, forming the compressed wood pellets. The freshly manufactured pellets are transferred to enormous storage silos to cool and solidify before being sent to port facilities.

Finally, the pellets are loaded onto trucks and transported to the transit facility, housed in specifically designed and built domes capable of holding 40,000 metric tonnes. This is the last stop for the pellets before they are shipped. (Drax Group plc, 2021)

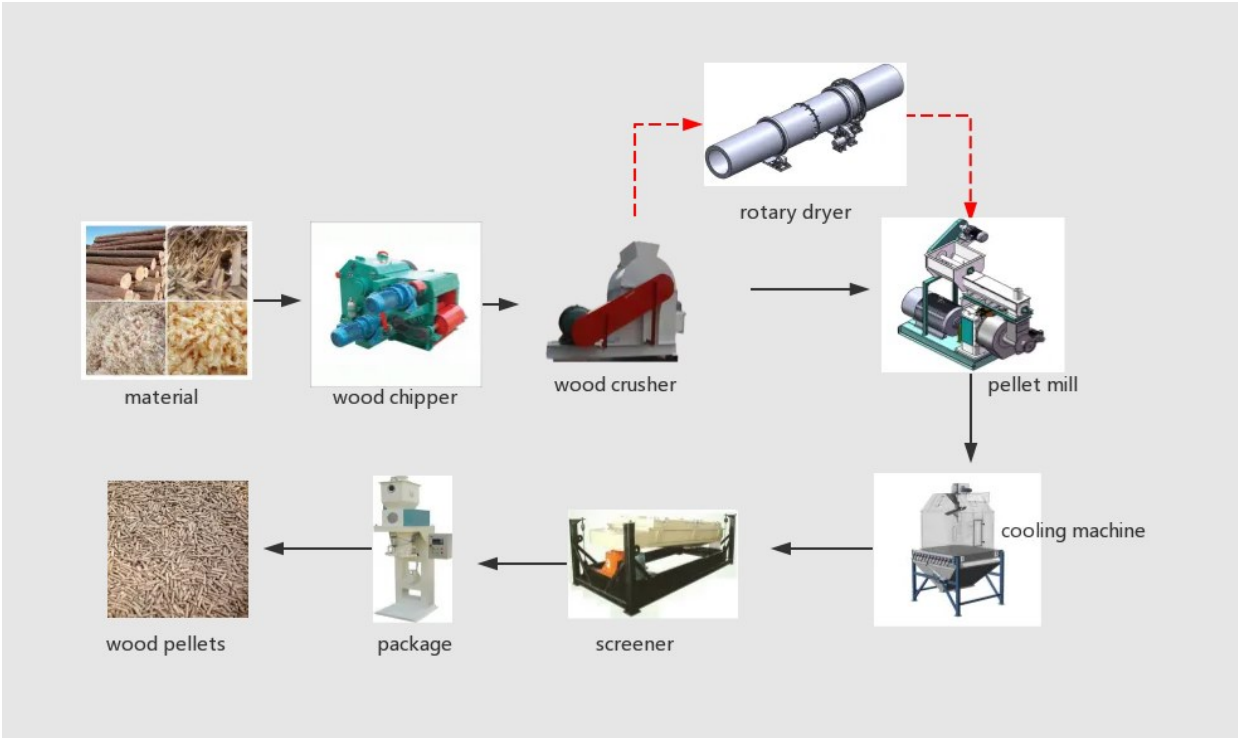

Figure 7 Process of Making Wood Pellets (Yuan, 2020)

2.3.1.2 Canadian Wood Pellet Market

Canada is the world's third-largest country in terms of forest area, with nearly 362 million hectares of forest, the majority of which is situated in the boreal region. This forest is made up of approximately 280 million hectares of various ecosystems, including lakes and wetlands. According to Canada's National Deforestation Monitoring System, less than half a percent of Canada's forest area has been deforested since 1990, indicating a successful conservation effort (Canada, 2023).

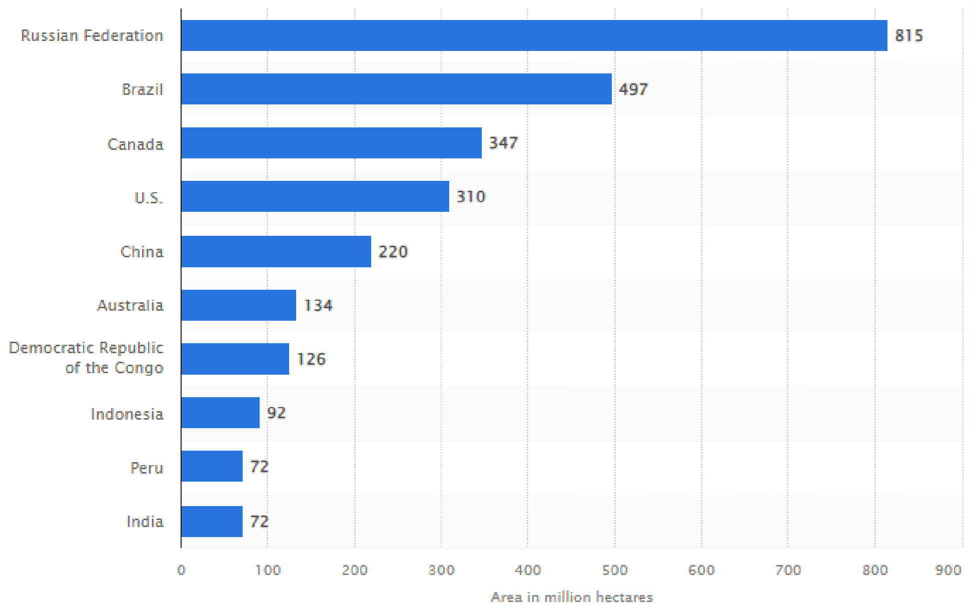

Figure 8 Ten countries with the largest forest area in 2020(in million hectares) (Shahbandeh, 2022)

Canada's forests are managed sustainably, with strict environmental regulations and extensive third-party certification, making them some of the most resilient forests in the world. This makes the Canadian wood pellet industry a reliable source of sustainable biomass products. The primary goal of the industry is to make the best use of forests that have already been harvested. By processing a wider range of wood fiber, the industry supports government-led initiatives to rehabilitate damaged, dead, or understocked stands, allowing new forests to be planted, enhancing wildlife habitats, and reducing carbon dioxide levels (Cools, 2020).

Canada faces significant economic and environmental challenges due to its dependence on low-cost natural resource commodities and associated GHG emissions. However, by employing clean and sustainable technologies and processes, Canada has the potential to become a leader in reducing GHG emissions while also boosting its economy (Stephen et al., 2016). This study explores how biomass, including forest and agriculture, can contribute to Canada's climate mitigation plan, lowering GHG emissions.

According to the Canada Energy Regulator and Natural Resources Canada, the combined use of biomass and geothermal energy sources accounts for a mere 1.4% of electricity generation across Canada. However, Natural Resources Canada reports that forest biomass alone contributes approximately 5-6% to the nation's overall energy supply. Natural Resources Canada reported in 2018 that 23.3 percent of the renewable energy produced in Canada originated from solid biomass, such as wood pellets (Watters, 2023).

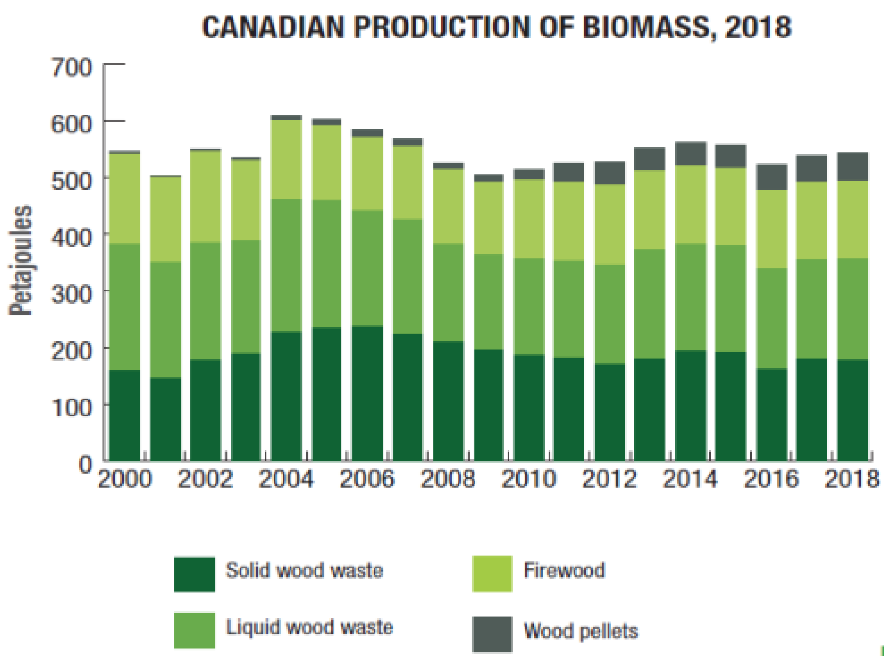

Figure 9 The Production of Woody Biomass in Canada (Watters, 2023)

According to the 2020 bioheat survey commissioned by Natural Resources Canada, wood pellets are the primary source of solid fuel bioheat installations in Canada, with their usage being particularly prominent in New Brunswick, Ontario, and the Northwest Territories. Wood pellets are more frequently used in Eastern Canada and BC's west coast, which may be attributed to their proximity to forested areas and significant population centers. This availability of wood pellet feedstock and higher energy demands concentrated in these regions could explain their widespread use (Watters, 2023).

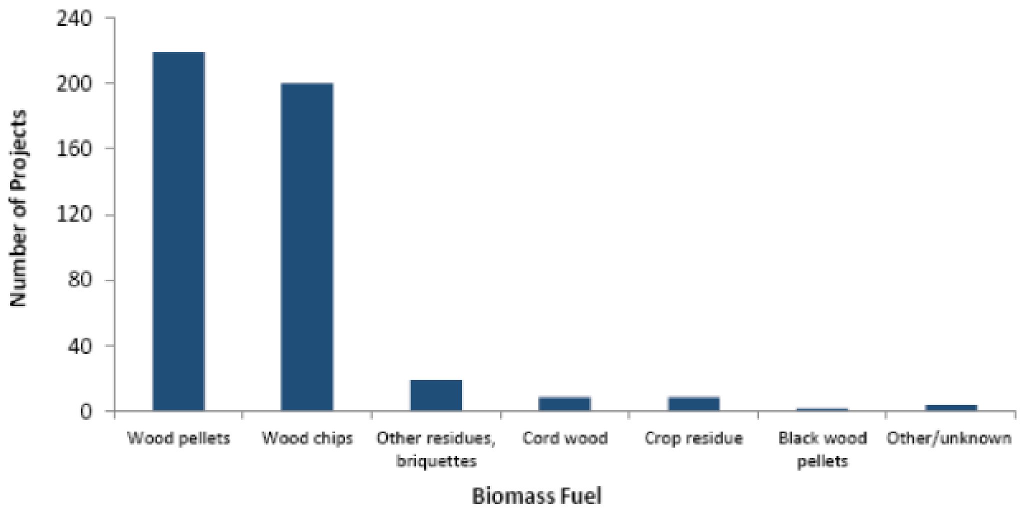

Figure 10 Bioheat Survey Report 2020 (Watters, 2023)

2.3.1.3 Wood Pellet in BC

BC is the world's leading subnational producer of wood pellets, with Asia and Europe importing 99 percent of the province's annual production of 2.5 million tonnes (Cools, 2020). The Wood Pellet Association of Canada (WPAC) has played a key role in promoting the use of B.C.'s wood pellets as a renewable alternative to fossil fuels, resulting in a reduction of approximately four million tonnes of CO_2 emissions per year. This represents about six percent of B.C.'s total GHG emissions.

Figure 11 BC's wood pellet exports grew by 1.2 billion kilograms between 2012 and 2020 (Westphal, 2021)

BC and Quebec have the highest number of pellet mills in Canada, surpassing all other provinces. In fact, BC alone accounts for 45 percent of the country's production capacity, which is more than double that of Quebec (Watters, 2023).

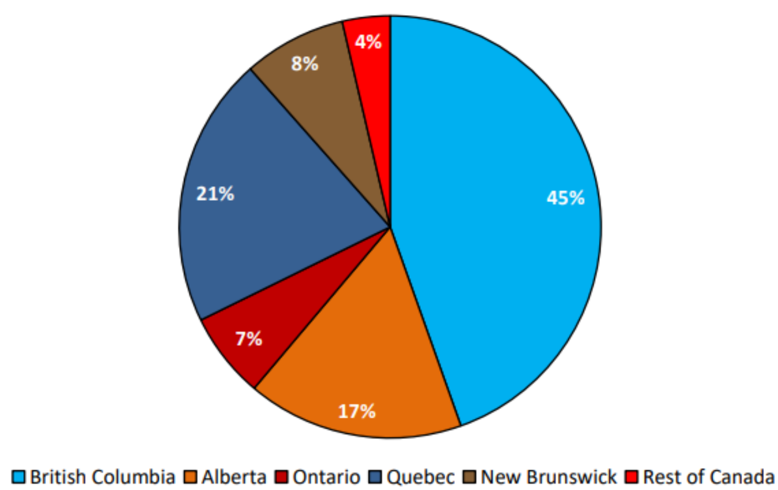

Figure 12 2021 Canadian Pellet Mill Production Capacity by Province (Watters, 2023)

The export of wood pellets is not environmentally friendly due to the significant amount of energy consumption and air emissions involved. An LCA conducted on the production and export of wood pellets from BC to Sweden found that for every tonne of wood pellets produced and shipped to Europe, about 7.2 GJ of energy is consumed, representing 39% of the total energy content of the pellets (Magelli et al., 2009). Long-distance ocean transportation is the main contributor to environmental and health impacts, with high fuel consumption resulting in emissions of harmful pollutants such as sulfur dioxide (SO_2), nitrogen oxides (NO_x), and particulate matter (PM). The emissions from ships are much greater than those from almost any other mobile source, which is concerning given the importance of shipping in the global economy. Despite being an efficient means of transportation for goods, the negative environmental impact of shipping wood pellets over long distances is significant (Magelli et al., 2009).

Figure 13 British Columbia wood pellets travel along this common shipping route to England (Westphal, 2021).

Using wood pellets for domestic purposes instead of exporting them can bring about various advantages. Firstly, it can lessen the negative impact on the environment that results from long-distance transportation. Secondly, the use of wood pellets domestically can foster the growth of a sustainable and local forestry industry. This can lead to economic gains, job creation, and support for the local economy. This study focuses on the use of domestic wood pellets in Canada, particularly in remote regions in need of diversifying energy sources.

2.3.1.3.1 Wood Pellet Feedstock Sourcing in BC

After conducting a thorough analysis of relevant government and industry databases, it was determined that approximately 78% of the residual feedstock presently utilized in BC pellet plants is sourced from sawmills. The major components of this feedstock include sawdust (40%), planer shavings (35%), bark hog (15%), pulp chips (6%), and other miscellaneous waste wood fiber (1%), all of which are by-products generated within sawmills. An additional 6% of the current residual feedstock originates from waste veneer strips obtained from plywood plants, fines resulting from the screening of wood chips at pulp mills, and trim ends from remanufacturing plants. The remaining 1% consists of waste wood fiber obtained from whole log chipping operations and the cleanup process of log yards at various wood processing plants situated throughout the interior region (Bull et al., 2022).

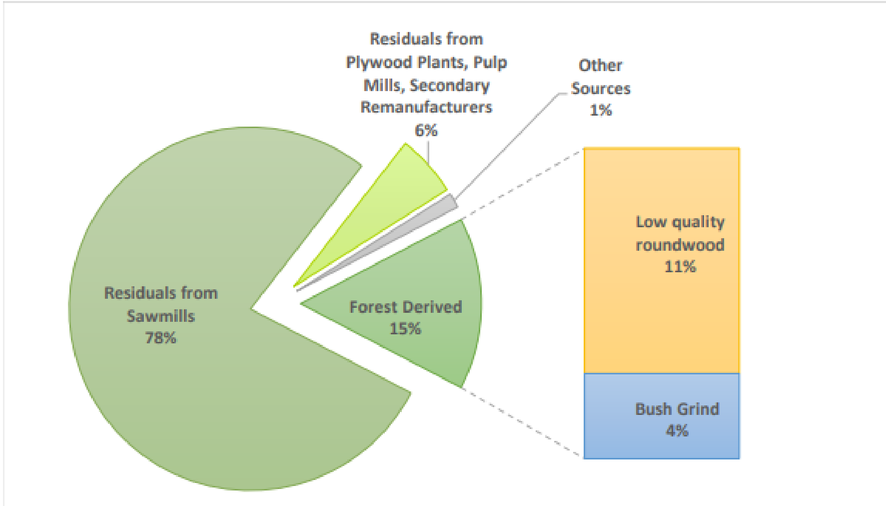

Figure 14 Feedstock Sources of BC's Pellet Plants from 2017 to 2021 (Bull et al., 2022)

2.3.2 Comparison of Main Types of Woody Biomasses

In this section, we will conduct a comparative analysis between wood pellets and two other prominent types of woody biomasses. By undertaking this comparison, we aim to provide a more comprehensive understanding of why conventional wood pellets were chosen as the focus of this study.

2.3.2.1 Torrefied Versus Conventional Pellets

Torrefied wood pellets, also known as black pellets, are a type of condensed renewable fuel produced by subjecting solid biomass to thermal treatment. These pellets are typically cylindrical in shape, ranging from 5 to 40mm in length, with a diameter of up to 25mm and broken ends. The primary raw material used for producing torrefied pellets is sawdust, although other palletizable feedstocks such as bark, miscanthus, or agricultural residues can also be used (ETIP Bioenergy, 2020)

The following diagram illustrates the emissions associated with the production and supply scenarios of conventional and torrefied pellets in Canada, considering their export to Finland. It is evident from the diagram that the production of torrefied pellets generates significantly higher emissions compared to conventional pellets. However, when considering the entire lifecycle, torrefied pellets exhibit lower emissions in terms of end use and transportation.

The higher emissions during torrefied pellet production can be attributed to the thermal treatment process involved in their creation. This process requires additional energy and resources, leading to increased emissions during the torrefaction phase. On the other hand, conventional pellet production involves less energy-intensive processes, resulting in comparatively lower emissions during this stage (Agar et al., 2015).

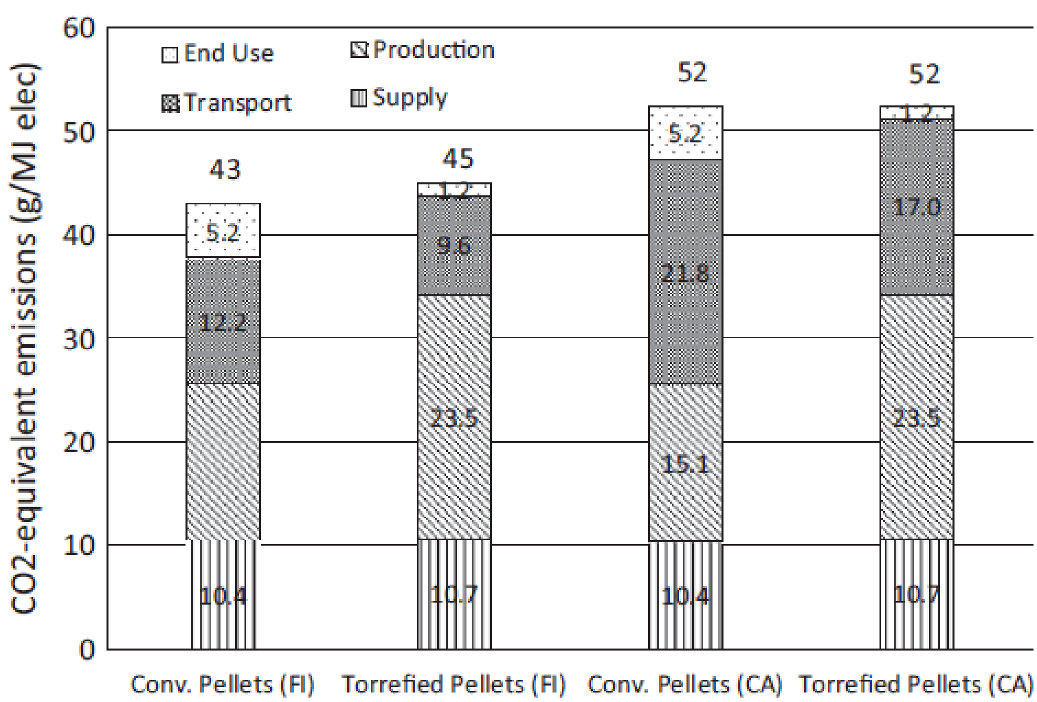

Figure 15 Comparison of Total Emissions from Conventional and Torrefied Pellets in Finland (FI) and Canada (CA) (The end user is Finland) (Agar et al., 2015)

Torrefaction enhances the calorific value of the feedstock, leading to increased energy density in pellets. The required distance for product transport to achieve lower CO_2-equivalent emissions for torrefied pellets compared to conventional pellets depends on the transportation method. Figure 16 presents the total emissions of both types of pellets based on lorry transport distance (assuming no other transportation modes). The point of intersection between the two lines (401 km) indicates equal emissions. Beyond this distance, torrefied pellets have lower total emissions from production and use compared to conventional pellets. Similar equations are available for other transportation modes, with intersection points at 1844 km (rail) and 25,650 km (ship) (Agar et al., 2015).

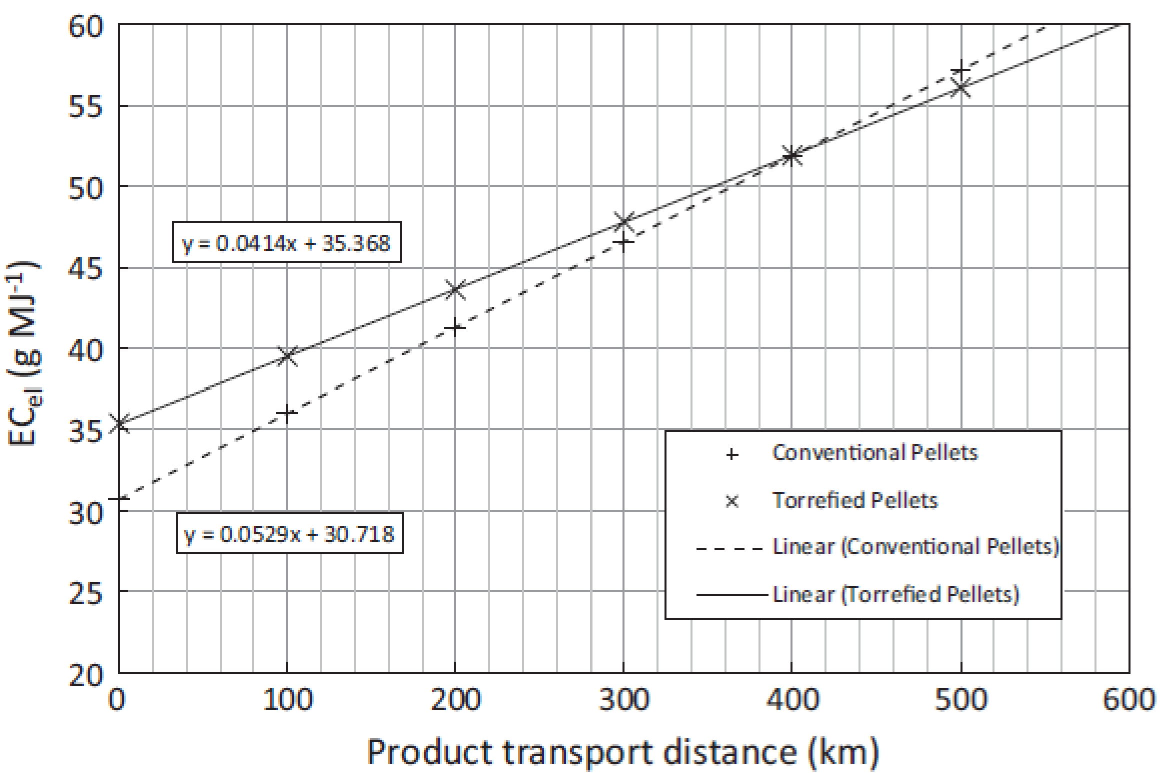

Figure 16 CO_2-Equivalent Emissions of Conventional and Torrefied Pellet Production: Impact of Lorry Transport Distance on Final Energy Commodity Emissions (Agar et al., 2015)

Despite all the benefits, the challenges associated with using torrefied wood pellets are as follows (Patchell, 2019):

- Energy and Cost: Torrefaction is an additional step in the feedstock preparation process that requires energy, which translates to additional costs for pellet production.
- End-Product Quality Variations: The specific conditions employed during torrefaction can lead to inconsistencies in the quality of the product. Variations in feedstock particle size and moisture content can result in uneven carbonization, with smaller pieces turning into charcoal while larger pieces remain under-torrefied.
- Particle Size Limitations: Small particles pose limitations for certain torrefaction technologies as they can cause clogging and obstruction of gas flow, impacting the efficiency of the process.
- Control of the Reactor: Achieving the right dynamic time and temperature strategy to manage moisture, particle size, and volatile content in the reactor is a challenge. Fouling in the reactor vessel and inefficient use of volatile calorific content within the gas loop can occur.
- Safety Concerns: Densifying torrefied materials involves handling high feedstock temperatures and highly reactive dust, which can present a risk of explosions and fires.
- Technical Accommodations: Incorporating torrefaction into existing pellet manufacturing facilities requires addressing technical factors such as preventing condensation of natural wood extractives in the gas loop and handling sawmill residuals with varying particle sizes.

- Die Life and Lubrication: Using torrefied material in standard pellet mills can result in a shorter die life due to the increased hardness of torrefied pellets compared to untreated wood. The use of binders may be necessary for die lubrication in order to mitigate this issue.

Additionally, there is currently uncertainty in the market regarding the specifications and degree of torrefaction required for torrefied material, indicating a need for further clarity and standardization in this area (Patchell, 2019).

2.3.2.2 Wood Chips Versus Wood Pellets

Wood chips are small, specially crafted pieces of wood that are commonly utilized in pulp mills. They are produced by cutting logs and leftover wood materials from the production of solid wood products like lumber and plywood. The desired dimensions for wood chips typically fall within a range of 4-6 mm in thickness and 15-20 mm in length and width. These dimensions are carefully chosen to facilitate the uniform reduction of wood into individual fibers and fiber bundles within batch and continuous chemical and mechanical pulping systems. It is important to note that due to the natural variability of wood, it is challenging to create a "perfect chip" that can be consistently reproduced with identical characteristics (Fuller, 2004).

Based on the provided figure, which shows the CO_2 emissions variation for the entire production chain per MWh of useful energy generated in the conversion plant, the comparison between wood pellets and wood chips reveals that the wood pellet route has better environmental performance, particularly when using a small cogeneration plant. Figure 17 demonstrates that the environmental impacts of both routes are relatively similar. However, when considering a small cogeneration plant, which typically has higher exergetic efficiency (ranging from 25% to 80%), the wood pellet route exhibits better results in terms of CO_2 emissions (Pereira et al., 2018).

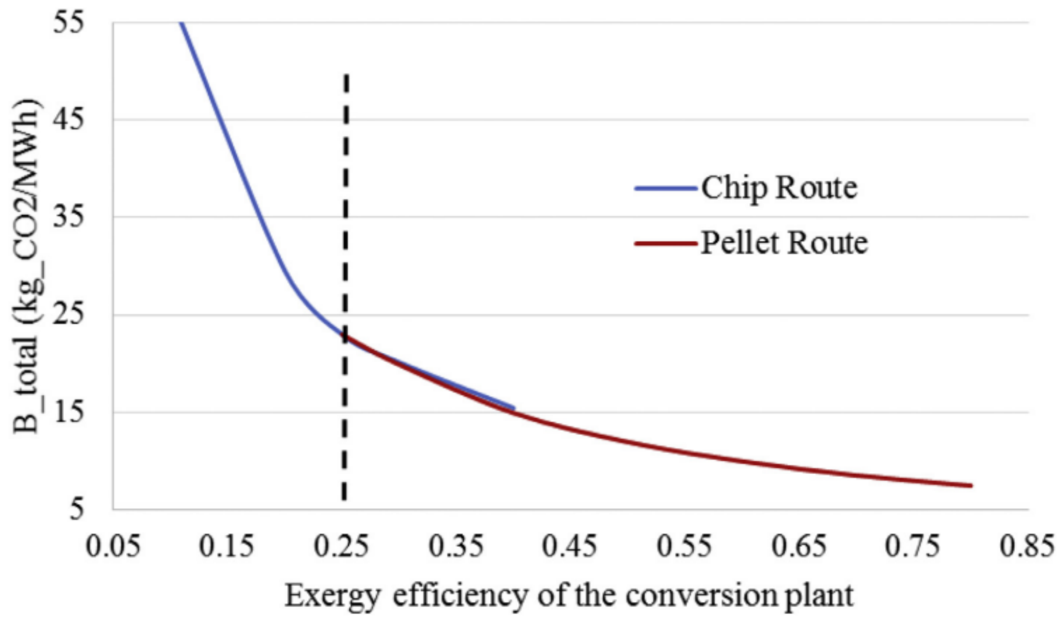

Figure 17 CO_2 Emissions Variation with Conversion Plant Exergy Efficiency (Pereira et al., 2018)

Based on the analysis comparing wood chips and wood pellets for biomass fuel applications, wood pellets demonstrate certain advantages. Both wood chips and wood pellets have similar CO_2 emission impacts of approximately 24 $kgCO_2$/MWh, indicating a low environmental impact. However, the wood pellets route results in around 15% more destroyed exergy compared to the wood chips route, suggesting slightly higher exergy destruction. Nevertheless, the pellet route offers greater flexibility for cogeneration plants, making it a more favorable choice for biomass conversion into energy. Overall, wood pellets have advantages in terms of flexibility for cogeneration and relatively low CO_2 emission impacts, making them a preferable option for biomass fuel applications compared to wood chips (Pereira et al., 2018).

2.3.3 Air Quality and Woody Biomass

Fossil fuels originate from the decomposition of carbon-based organisms that occurred over extensive periods of time. These resources, namely coal, oil, and gas, are finite in nature and cannot be replenished. They play a significant role in generating around 80% of the world's energy and find application in the production of diverse goods. However, when fossil fuels are burned, they release substantial amounts of carbon dioxide, a GHG that contributes to global warming. This has already led to a one degree Celsius increase in the average global temperature, risking sea-level rise, extreme weather events, biodiversity loss, food scarcity, health issues, and poverty for millions of people worldwide. The impact of fossil fuels on the air quality and climate calls for urgent action towards cleaner and more sustainable energy alternatives (ClientEarth, 2022).

In contrast, wood biomass is a sustainable energy source that has the potential to reduce GHG emissions. Trees are a renewable resource, and if harvested areas are regrown, wood biomass can be considered a renewable energy source. When wood is burned, it releases carbon dioxide into the atmosphere. However, replanting trees to replace harvested ones absorbs carbon, making wood biomass a "carbon neutral" energy source (Wood-Energy, 2019).

Although wood-fired power plants generate greater amounts of particulate matter compared to coal and gasoline, it is the most manageable form of emission. With the implementation of pollution-control devices such as scrubbers, filters, and catalytic converters, the levels of particulate matter can be significantly reduced (Wood-Energy, 2019).

2.4 Life Cycle Assessment

LCA is a concept that emerged in the 1960s as a response to growing concerns about environmental degradation and resource scarcity. Initially, LCA studies were focused on packaging and limited to energy use and a few emissions, primarily for companies, with little communication to stakeholders. However, the 1980s and 1990s saw a surge in methodological development and international collaboration in the scientific community, making LCA applicable to a wide range of products and systems. Today, LCA continues to evolve, with increasing emphasis on building international scientific consensus and standardization. LCA is a tool used to assess the environmental impacts of a product or system throughout its entire life cycle, from raw material extraction to disposal, and is increasingly commissioned by both industry and governments (Bjørn et al., 2017).

2.4.1 Background

The International Organization for Standardization (ISO) is a voluntary and global federation of national standards agencies (Loshin & Steele, 2021). ISO has developed several standards related to LCA to promote consistent and credible environmental assessments. The most well-known standard is ISO 14040, which provides general principles and guidelines for conducting LCA studies. All four stages of LCA are covered in ISO 14040 (Lee et al., 2004).

The LCA is a method for assessing how products and decisions impact the environment (Cowie et al., 2019). Using LCA can be beneficial as it provides information about a product's environmental impact before it is marketed, which can help prevent underestimation. The steps in LCA are presented as follows (Cowie et al., 2019):

1) Goal and scope definition: The study's goal and scope are defined before collecting any data. LCA methodology's approach is determined in this phase, which is very important. However, the goal and scope can be modified as data are collected. (Curran, 2016)

2) Life Cycle Inventory analysis (LCI): The data collection process for conducting an LCA commences once the demarcation lines have been established. During the LCI stage, the inputs and outputs of an industrial system are quantified and documented, considering the specified functional unit.

3) Life Cycle Impact Assessment (LCIA): The LCIA is the process of making the data collected in the LCI phase meaningful and actionable. Using the data collected in the LCI phase, actual environmental impacts are calculated (Rochester Institute of Technology, 2020).

4) Interpretation of the results: Interpretation is the final step in the LCA study. It involves categorizing, quantifying, checking, and evaluating the LCI and LCIA outcomes. The interpretations will lead to appropriate conclusions and recommendations (Mohan, 2018).

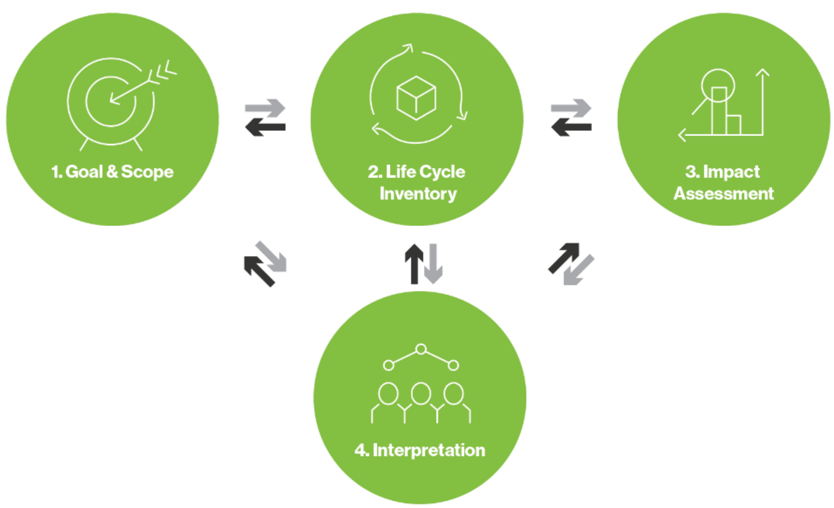

Figure 18 LCA Stages (RIT, 2020)

2.4.2 LCA standards

Standards provide a set of metrics that serve as a framework for comparison between products or organizations. It is essential for organizations to stay up to date with the latest LCA standards to keep abreast of global and regional advancements in sustainability reporting. This helps them to determine which standards are applicable to their sector and how to comply with them, enabling them to make practical and timely sustainability investments (Pallas et al., 2022).

ISO 14040 and ISO 14044 are the leading standards for LCA, which is a critical tool for assessing the environmental impact of products. ISO 14040 provides a framework for LCA and outlines key principles, while ISO 14044 provides detailed guidance on conducting an LCA and specifies the necessary requirements. Adhering to these standards ensures that LCA results are accurate, reliable, and comparable across different products and sectors (Pallas et al., 2022).

2.4.2.1 LCA Limitations

Companies are using LCA to lessen their environmental impact. These assessments evaluate the environmental effects of products, processes, facilities, and technologies. Various firms offer LCA services and follow ISO 14044 standards. However, even if an LCA complies with ISO standards, companies may not be aware of the limitations, uncertainties, or assumptions underlying it. Additionally, an LCA alone may not be adequate for marketing or disclosure purposes without being reviewed by a board for an Environmental Products Declaration (EPD) (James & Morrison, 2022).

LCA is widely used to evaluate the environmental impacts of products or processes. However, conducting an accurate LCA can be challenging due to various factors.

One challenge is that LCAs may rely on generalized data sets when evaluating emissions from a feedstock. Although databases providing emissions factors are commonly used, these values may not be precise for a particular supplier or chemical due to the different production processes and varying emissions treatments. Moreover, some chemicals may lack specific data, leading to approximation using data from other chemicals (James & Morrison, 2022).

One major drawback is the high cost associated with conducting a comprehensive LCA, making it economically prohibitive for many organizations. The process is data intensive and time-consuming, with costs further increased by the need for professional consultation and expert knowledge during impact and improvement analyses (Envirotrain, 2018).

In some cases, LCA studies focus only on specific stages of a product or process's life cycle, rather than considering the overall life cycle. This limited scope restricts the conclusions that can be drawn and compromises the realism and usefulness of the results. Environmental parameters analyzed in some studies may also be insufficient, often omitting aspects like land use, biodiversity, and other environmental impacts of energy consumption and waste generation (Envirotrain, 2018).

Comparative LCAs, which compare two products or processes, may not always provide accurate comparisons. The reliability of these comparisons can be affected by unreliable data for conventional technologies, outdated or regional data, and assumptions made by investigators. Companies have many options to reduce environmental impact beyond what is presented in a comparative LCA, and LCA studies often consider various impacts, presenting trade-offs or co-benefits beyond a reduced carbon footprint (James & Morrison, 2022).

Chapter 3: Description of the Case Study

For the Canadian forest sector, wood pellets are a modest but essential market. The majority of pellets are made from industrial waste, sawmills, and wood production enterprises. Timber harvest wastes are another source of biomass for wood pellet manufacture. In Canada, a tiny percentage of wood pellet production is used for domestic heating and electricity generation (about 100,000 to 200,000 tonnes). The vast majority of this fuel is shipped across the world (Canada, 2020). In BC, the wood pellet industry contributes greatly to the development of sustainable bioenergy sources. It was reported in a 2020 article published in the Canadian Biomass magazine that BC was the world's largest producer of wood pellets, exporting 99 percent of its 2.5 million tonnes that year (Watson, 2021).

In Canada, pellet boiler systems cannot be sold due to administrative barriers. At the moment, Canada does not manufacture the boilers, nor can import them as they are manufactured, so Canada's pellets are only available offshore, to be used as renewable energy and heat in homes and businesses all over the world. As a result of the lack of modern highly automated wood pellet boilers, Canada's wood pellet consumption is tiny compared to the rest of the world.

For several years now, the Wood Pellet Association of Canada (WPAC) has been trying to resolve this unnecessary barrier, with Prince Edward Island and Ontario being the first places to make progress (Cools, 2022). Our study's goal is to demonstrate how other provinces like BC can benefit from using wood pellets as a renewable energy source to replace fossil fuels. Canadian rural areas would benefit from lower heating costs and reduced GHG emissions, resulting in hundreds of new jobs. (Jiggens, 2022)

To evaluate using the BC pellets for the remote communities in this province we used information from CanmetENERGY, a division of Natural Resources Canada's report which conducted phone interviews with nine pioneering rural and distant communities that have implemented biomass heating and CHP systems in early 2020 to learn about their experiences (Madrali & Blair, 2020).

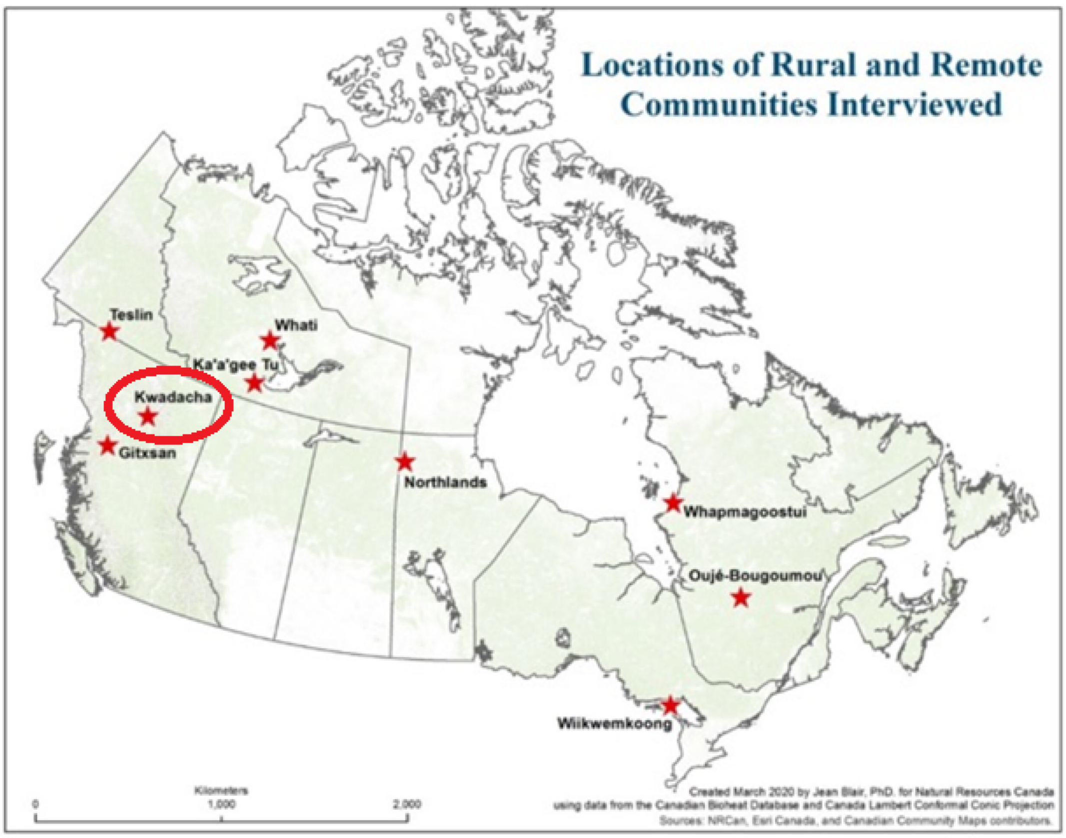

Figure 19 Locations of remote communities considered in the conducted interview (Madrali & Blair, 2020)

Our study specifically focuses on the Kwadacha First Nation, a remote community located in Fort Ware, BC. This community, situated approximately 570 kilometers north of Prince George, is only accessible by logging roads or air transportation. Since 2017, the community has been utilizing a biomass plant, primarily powered by wood chips (Electricity Canada, 2022). However, we recognize the numerous benefits associated with using wood pellets instead of wood chips, as discussed in the previous chapter. Considering that the community continues to rely on diesel, we have chosen to concentrate on this remote community to highlight the advantages of using wood pellets, particularly in terms of small cogeneration plants. The findings of our study can also be relevant for other nearby remote communities, such as Tsay Keh Dene, creating potential opportunities for widespread implementation of wood pellet usage in these areas.

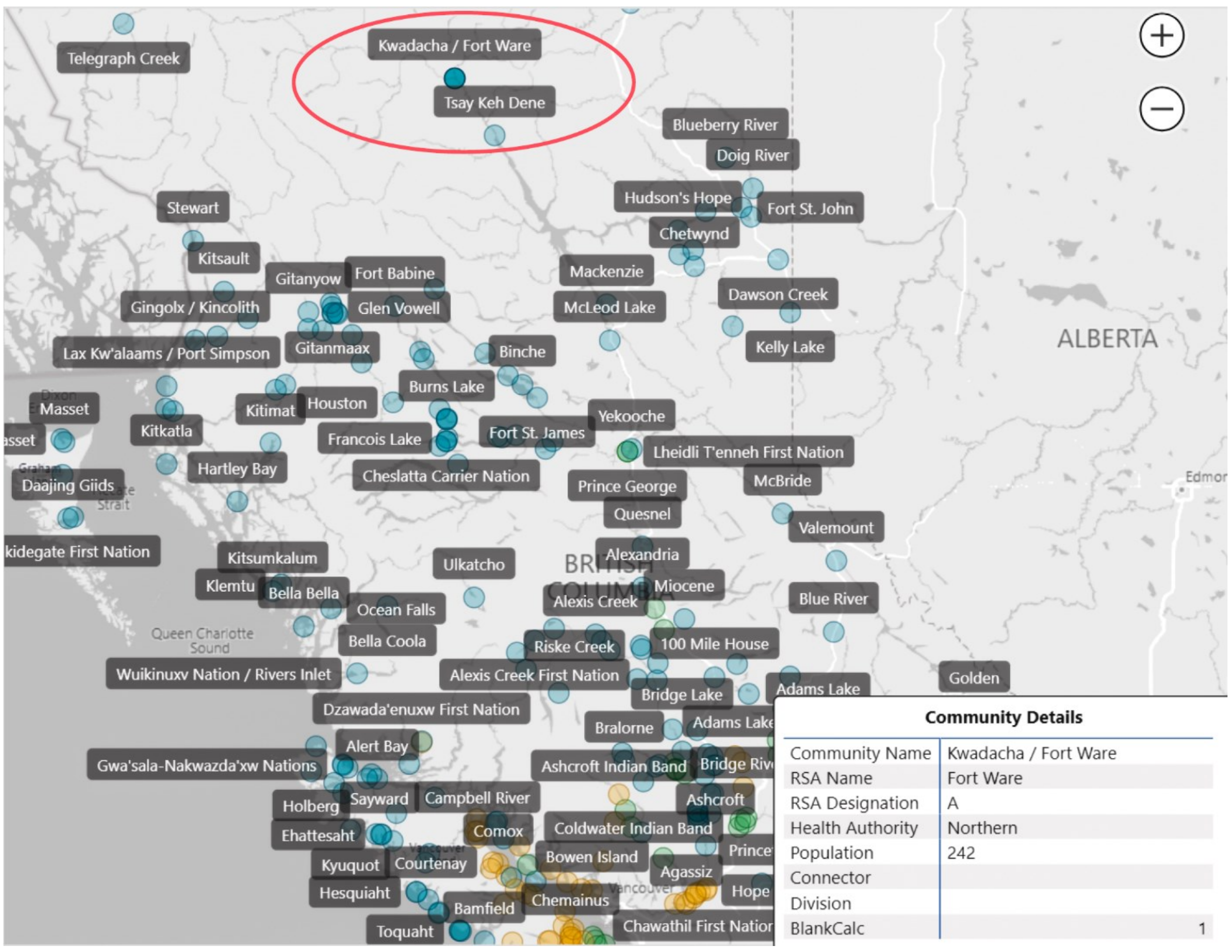

Figure 20 Map of Rural Communities (RCCbc, 2023)

Chapter 4: Methodology

4.1 Goal of the Study

The primary objective of this study is to conduct an LCA on wood pellets derived from both pine and spruce trees. The purpose of this assessment is to identify and evaluate the environmental impacts associated with the use of these wood pellets as a substitute for fossil fuels in remote communities located in BC, Canada. By undertaking this analysis, we aim to gain insight into the sustainability of this alternative energy source and its potential to reduce GHG emissions and other negative environmental impacts.

4.1.1 Scope Definition

4.1.1.1 Functional Unit

The functional unit plays a crucial role in the LCA methodology by serving as a fundamental point of reference for all impact assessment calculations. Its definition occurs during the initial phase of LCA, known as the goal and scope definition stage. The functional unit is a quantification of the function of a product and should be carefully chosen to accurately represent the use and benefit of the product. (Arzoumanidis et al., 2019)

We adopted the functional unit of one tonne of wood pellets for this study. Selecting one tonne of wood pellets as the functional unit offers several advantages in assessing the environmental impacts associated with wood pellet production and use. Firstly, it provides a standardized and consistent unit of measurement, enabling accurate comparisons across different wood pellet production processes and comparisons with other energy sources. Furthermore, the use of one tonne as a functional unit aligns with industry practices, facilitating the integration of our findings into existing LCA studies. Lastly, one tonne of wood pellets represents a substantial amount of energy, rendering it a relevant and meaningful unit for evaluating the environmental implications of wood pellets as an energy source.

4.1.2 System Boundary Description

Figure 21 illustrates the LCA boundary, and the processing stages and transportation segments involved in delivering wood pellets (produced in BC) to remote communities. The functional unit of this system is one tonne of wood pellets. The system boundary for a cradle-to-gate LCA of wood pellets typically includes the major stages of the product life cycle, namely the harvesting of timber, sawmill operation, pelletization, and combustion. This means that the LCA would cover the environmental impacts associated with the production of wood pellets, from the extraction of raw materials to the point of sale or delivery to the customer. The boundary would include activities such as forest management, timber harvesting, transport of raw materials to the sawmill, processing of timber to create wood chips, drying and pelletization of wood chips to form pellets, transport of pellets to the end user, and combustion of pellets for energy generation. Given the above-described boundary, neither land use changes nor building infrastructure changes are considered in this LCA.

More than 60% of BC's land is covered by forest, and less than one-third of 1% of BC's forests is logged annually. For logging purposes, no land is generally converted into forests (Pa et al., 2011). By excluding the end-of-life disposal phase, the LCA will not also include the environmental impacts associated with the disposal of residues after the combustion of wood pellets. The LCA adopted in this study can provide valuable information to identify opportunities for improvement in the production process and help decision-makers understand the environmental trade-offs of using wood pellets as a fuel source.

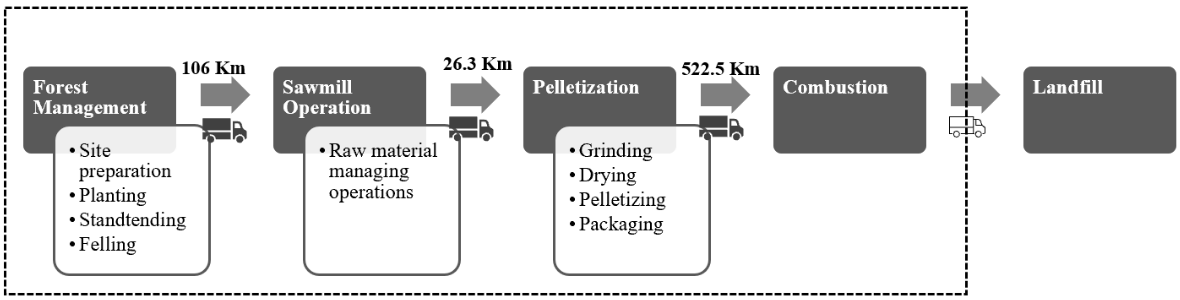

Figure 21 LCA System boundary

4.2 Life Cycle Inventory Data

LCI is a critical element of LCA that involves gathering and assessing data on the inputs and outputs across all stages of a product or a service. LCI provides a comprehensive understanding of the environmental impacts associated with the product or service, including energy and resource use, emissions to air, water, and soil, and waste generation. However, performing the inventory analysis is a time-consuming task. Although there are software platforms and databases (such as SimaPro) exist that offer a wealth of secondary data (SimaPro, 2021), some materials or processes might still be missing. In this regard, several approaches exist to address such data gaps, depending on the available resources and time.

Within the realm of LCA data, it is useful to distinguish between two types of data: primary data, which is self-generated through surveys, interviews, and experiments, and secondary data, which is stored as part of an organization's records and can be extracted from various data files. In this study, secondary data was primarily used from sources such as literature, surveys, online databases, and SimaPro's Ecoinvent database (SimaPro, 2021). The collection of energy consumption data for each stage of processing and transportation is the first step, including various types of energy consumption such as diesel, electricity, natural gas, wood residue, heavy fuel oil, propane, steam, and gasoline. The Ecoinvent database, which provides primary energy requirements for different fuels and energy, was utilized to comply with ISO 14040 and 14044 standards. Ecoinvent is considered as the largest and most consistent LCI database that supports data transparency (SimaPro, 2021).

4.2.1 LCI Parameters for Harvesting and Forest Management

LCI parameters for harvesting and forest management typically include a range of inputs and outputs associated with timber extraction, transportation, and processing. These parameters can vary depending on the specific practices used in each region or country. The Athena Sustainable Materials Institute (Athena, 2018) notes that Spruce and pine are among the most common tree species in Canada for producing wood pellet, which are the focus of this study. The data for these tree species was obtained from the Ecoinvent database using SimaPro software. After forest residues are transported to the pellet factory, any materials that cannot be utilized in pellet production, such as tree bark, are combusted to generate the heat required for raw material drying.

Table 1 Materials and processes for the forest management stage

Materials and Processes	**Amount**	**Unit**
Tree seedling, for planting (tree seedling production, in heated greenhouse)	0.0058212	p
Tree seedling, for planting (tree seedling production, in unheated greenhouse)	0.013845015	p
Gravel, crushed	0.020153085	kg
Harvesting/bundling, (energy wood harvester)	0.000361618	hr
Power sawing, (without catalytic converter)	0.000187535	hr
Forwarding	5.38818E-5	hr
Harvesting, (forestry harvester)	0.000341521	hr
Diesel, (burned in building machine)	0.015142181	MJ

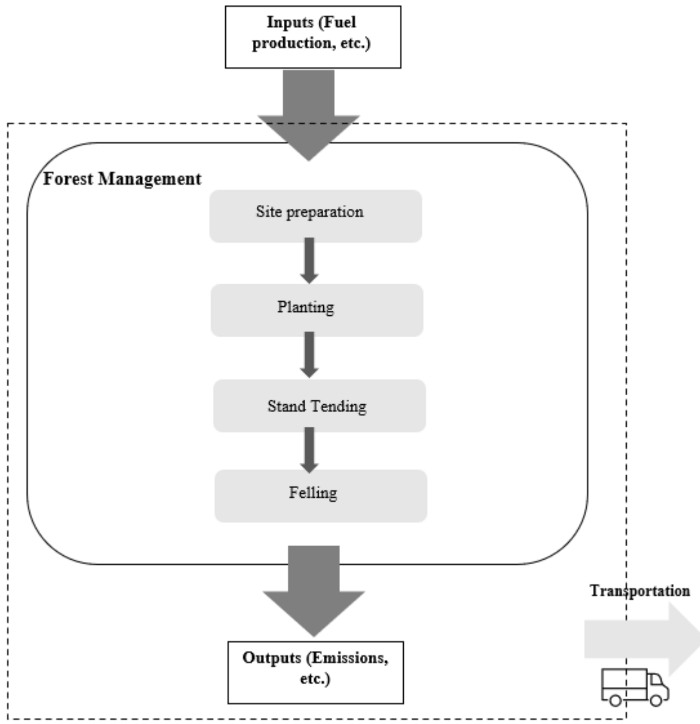

Figure 22 System boundary for forest management stage

4.2.2 LCI Parameters for Transportation

The LCI parameters that are associated with transport of feedstock to produce wood pellets encompass a variety of inputs and outputs that are involved in the logistics of raw materials from their origin, such as forests or other sources, to the processing facility. These parameters may include factors such as distance, fuel consumption, vehicle type, payload capacity that contribute to environmental impacts of pellet transportation.

Alternative transportation modes and distances for the feedstock delivery and their appropriateness is investigated as according to the Government of Canada (2013) and studies on LCA models and methodologies adopted for exported wood pellets from Canada to Europe (Magelli et al., 2009). According to these references, trucks are considered as the most suitable transportation mode, considering that the pathways do not have access to sea or other water bodies, and a distance of 100 km is assumed between the feedstock source and the production facility. However, it should be noted that in many cases, wood pellet facilities are located near forestry harvest operations and sawmills, which may result in shorter transportation distances, which are not only beneficial in terms of economic viability, but they also contribute to improved sustainability of biofuels due to reduced transport related environmental impacts (Government of Canada, 2013). The transport distance from sawmill to pellet production units is approximated as 26.3 km according to Pa et al. (2013) and Magelli et al. (2009).

After a thorough evaluation of multiple wood pellet production facilities in BC, the Premium Pellet facility stood out as the optimal choice. This facility has the capability to efficiently transport wood pellets to the Kwadacha community, which is situated approximately 522.5 km away on average. Premium Pellet has a production capacity of up to 170,000 metric tonnes of pellets. It is mainly a supplier to power industry in BC to replace coal in electricity generation. It also serves customers for residential heating in BC (Sinclar Group, 2022). In comparison to other pellet producers, Premium Pellet is located relatively closer to the remote community of Kwadacha, resulting in reduced environmental impacts and costs associated with pellet transportation.

4.2.3 LCI Parameters for Sawmill Operation and Pelletization

The LCA of sawmill operation and pelletization is associated with a variety of inputs and outputs including energy consumption, raw material use, as well as chemicals and additives. Such parameters provide valuable insights into the conversion of raw materials, such as sawdust or wood chips, into wood pellets, and help to assess the environmental impact of such transformation processes.

Pa (2010) provided valuable data on sawmill operation and pellet production, which is used as a basis to develop a wood pellet inventory for BC and evaluate domestic pellet utilizations. The data we considered for this study encompassed energy consumption per tonne of wood pellets, measured in MJ, as well as emissions per tonne of wood pellets, measured in Kg. This information is an essential component in assessing the environmental impact of wood pellet production process and identifying areas for improvement.

Table 2 Materials and fuels input for the sawmill operation

Materials and Fuels	**Amount**	**Unit**
Electricity	186	MJ
Natural Gas	135	MJ
Heavy fuel oil	14.57	MJ
Diesel	42.86	MJ
Propane	3.68	MJ
Process steam	47.55	MJ
Dry wood combustion	271	MJ

Table 3 Emissions to air for the sawmill operation

Emissions to air	Amount	Unit
Carbon dioxide, fossil	1.97E1	Kg
Carbon dioxide, biogenic	2.67E1	Kg
Methane	4.46E-2	Kg
Methane, biogenic	2.55E-3	Kg
Dinitrogen monoxide	2.28E-3	Kg
Carbon monoxide	2.17E-2	Kg
Carbon monoxide, biogenic	7.26E-2	Kg
NMVOC, non-methane volatile organic compounds	1.28E-2	Kg
Nitrogen oxides	1.23E-1	Kg
Sulfur oxides	2.70E-2	Kg
Particulates, SPM	6.57E-2	Kg
Particulates, < 2.5 um	5.08E-4	Kg

Table 4 Materials and fuels input for the Pelletization stage

Materials and Fuels	Amount	Unit
Electricity	490	MJ
Diesel	23.49	MJ
Propane	6.16	MJ
Dry wood combustion	1059	MJ

Table 5 Emissions to air for the

Emissions to air	Amount	Unit
Carbon dioxide, fossil	8.33E0	Kg
Carbon dioxide, biogenic	1.02E2	Kg
Methane	5.06E-2	Kg
Methane, biogenic	9.81E-3	Kg
Dinitrogen monoxide	6.40E-3	Kg
Carbon monoxide	1.44E-2	Kg
Carbon monoxide, biogenic	2.80E-1	Kg
NMVOC	1.33E-2	Kg
Nitrogen oxides	1.58E-1	Kg
Sulfur oxides	1.89E-2	Kg
Particulates, SPM	2.07E-1	Kg

4.3 Impact Assessment

SimaPro provides several impact assessment methods for calculating impact assessment findings (SimaPro, 2021). For this research, TRACI 2.1, which is one of the North American impact assessment methods, is chosen. **TRACI** (Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts) is a stand-alone computer software designed by the Environmental Protection Agency. TRACI defines environmental stressors as ozone depletion, global warming, eutrophication, acidification, ecotoxicity, human health-related effects, tropospheric ozone (smog), human health cancer effects, human health non-cancer, fossil fuel depletion, and land-use effects (PRé Sustainability, 2020). These impact categories are relevant for wood pellet production, as they are associated with emissions from transportation, energy use, and other aspects of the production process. In addition, TRACI 2.1 includes several impact categories related to human health, such as respiratory effects, which can be important considerations for wood pellet production, particularly in areas where air quality is a concern.

Chapter 5: Results Analysis

The LCA analysis was conducted using SimaPro software version 8.4.0.0 and TRACI 2.1, and using Ecoinvent 3 and Agri-footprint databases with the objectives of:

1) Assessing the environmental impact of wood pellets adoption as a heating fuel on remote communities.
2) Comparing the environmental impacts of wood pellets versus diesel combustion.

Considering the above objectives, the LCA is conducted across the following stages:

5.1 Exploring SimaPro: An Overview and Application

SimaPro is a powerful LCA software that allows users to leverage their expertise in LCA to drive business value. With SimaPro, you can make informed decisions, optimize the life cycles of your products, and enhance your company's overall positive impact. This professional software tool enables you to efficiently collect, analyze, and monitor the sustainability performance of your products and services. SimaPro stands out for its flexibility and user-friendly interface, making it easy for both individuals and teams to navigate. Its multi-user version allows seamless collaboration, enabling teams to work together on a single database, even if they are located in different parts of the world. SimaPro offers multiple impact assessment methods and an extensive database, ensuring access to a wealth of data. The software's transparent results enable interactive analysis, allowing you to trace back any result to its source (LTS, 2023).

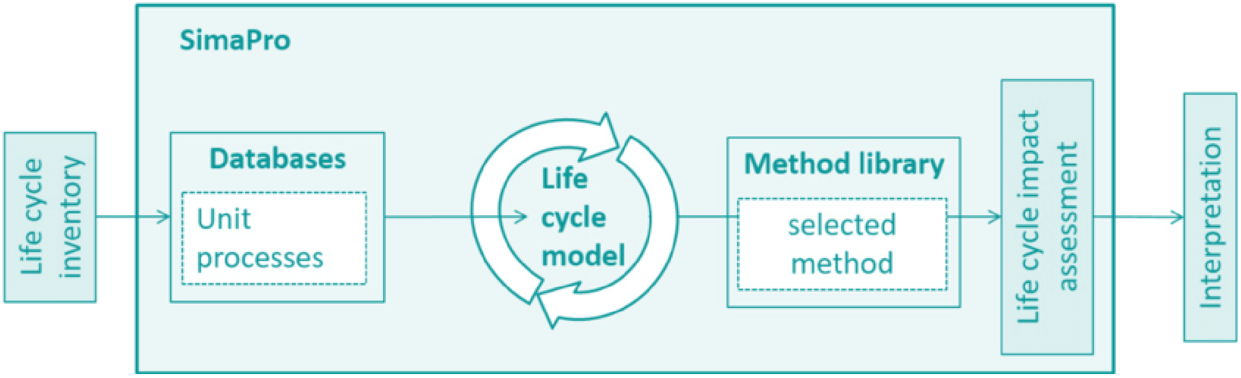

Figure 23 SimaPro (Almeida et al., 2018)

In this study, we utilized the Ecoinvent v.3 and Agri-footprint databases sourced from SimaPro. The Ecoinvent Database, known for its comprehensive LCI data, serves as a valuable resource for conducting sustainability assessments and understanding the environmental impacts associated with diverse products and services (ecoinvent, 2022). On the other hand, Agri-footprint, an extensive LCI database within SimaPro, specifically focuses on agricultural products, encompassing feed, food, and biomass (SimaPro, 2023).

5.2 Harvesting and Forest Management

Energy wood and forestry harvesting is a crucial stage in forestry with a significant impact on the environment. Energy wood harvested from forests is used in power plants and households. Tree branches, treetops, and stumps are commonly used as energy wood (UPM, 2021). Forest harvesting is carried out after a final felling before regrowth. This process involves cutting trees and delivering them to sawmills, pulp mills, and other wood-processing facilities. Forest harvesting involves construction of roads, logging, and transportation with impacts on the environment (Wellburn & Kuhlberg, 2010).

Table 6 SimaPro results for the forest management

Label	**Gravel, crushed**	**Harvesting/bundling, energy wood harvester**	**Power sawing**	**Forwarding, forwarder**
Ozone depletion	0.2616	50.7727	2.5111	4.8354
Global warming	0.239	51.1996	2.3873	4.4861
Smog	0.256	44.555	2.4599	7.0667
Acidification	0.299	46.8856	1.5077	6.1225
Eutrophication	0.4037	47.6333	3.6924	3.9472
Carcinogenics	0.8147	57.5142	1.3904	3.7235
Non carcinogenics	0.856	62.396		3.8678
Respiratory effects	0.3524	47.7586	1.968	4.2087
Ecotoxicity	0.5934	67.816	1.3248	2.7986
Fossil fuel depletion	0.2076	53.7287	2.4098	4.6064
Label	**Harvesting, forestry harvester**	**Diesel**	**Tree seedling (tree seedling production, in heated greenhouse)**	**Tree seedling (tree seedling production, in unheated greenhouse)**
Ozone depletion	36.7705	2.8445	0.6887	1.3155
Global warming	35.4704	2.5504	1.8774	1.7897
Smog	38.3838	5.9433	0.5312	0.804
Acidification	36.8495	4.8142	1.7489	1.7725
Eutrophication	33.549	2.1277	4.0126	4.634
Carcinogenics	31.4477	1.7272	1.652	1.7303
Non carcinogenics	26.7907	1.0904	2.5005	2.4985
Respiratory effects	32.9464	4.9577	2.9392	4.869
Ecotoxicity	21.8053	0.7642	1.9879	2.9098
Fossil fuel depletion	35.0562	2.6963	0.5047	0.7903

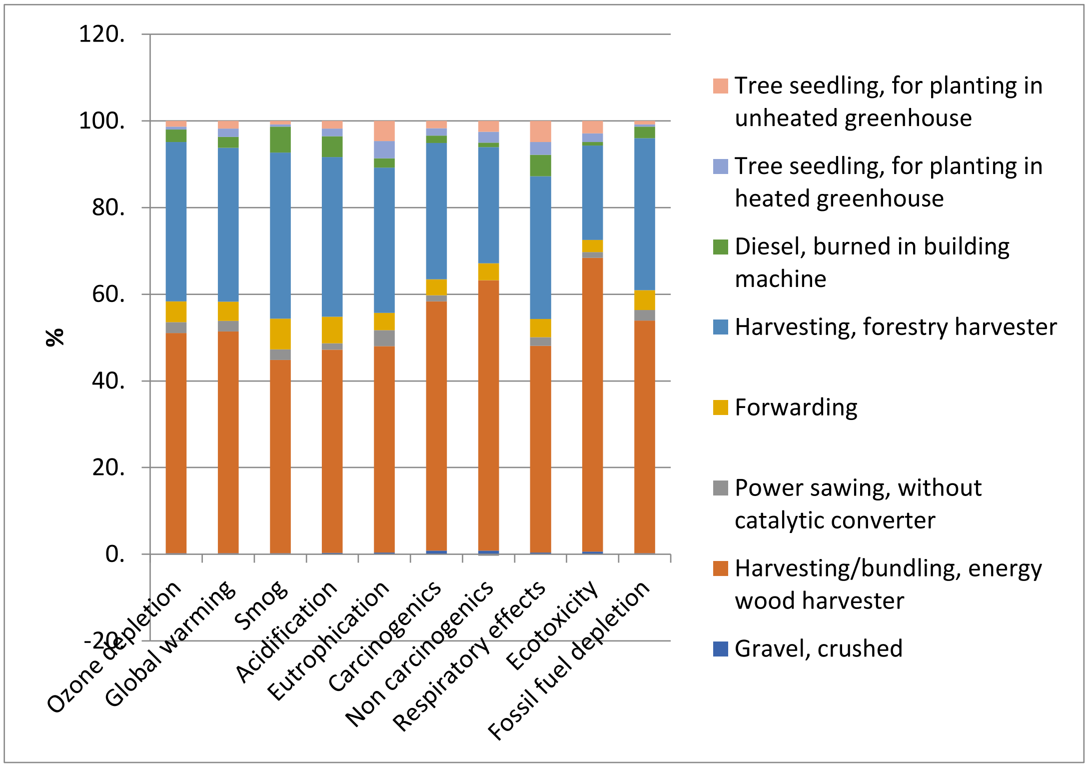

Figure 24 SimaPro results for harvesting and forest management

5.3 Transportation

The LCA results presented in Figure 25 clearly indicates that the transportation of wood pellets to remote communities is the primary contributor to environmental impacts of wood pellets. This is primarily due to a considerable distance between the pellet production facility and these remote areas. Transportation of feedstock to for sawmill operation is the second most significant contributor. Therefore, reducing transportation distances and optimizing logistics can significantly enhance the environmental sustainability of wood pellet production and distribution.

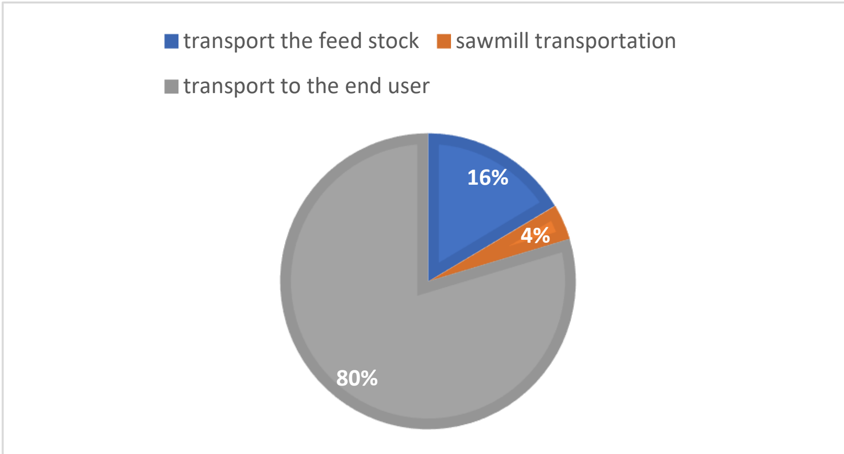

Figure 25 - The transportation scenarios considered in the LCA of wood pellets

5.4 Sawmill Operation

In sawmill operation, diesel usage has the highest impact on the environment, with electricity usage being the second most influential factor. While small-scale sawmills offer a range of power source options, including gasoline and electricity, diesel-powered units are often preferred due to their low cost. Thus, environmental impact of diesel usage should be carefully considered when selecting a power source option for sawmill operations (Kryzanowski, 2018).

Operations of a hardwood sawmill involve log debarking, log sawing, flitch edging, trimming, side-cuts chipping, and lumber drying. If the mill produces only rough green lumber and lacks kiln drying facilities, it will primarily rely on electricity. Otherwise, steam or combustion heat becomes the primary energy source. To improve energy efficiency, it is important to focus on using highly efficient motors in combination with energy utilities. This can help to reduce the overall energy consumption of the sawmill, regardless of what energy source being used. (Lin et al., 2012).

Table 7 SimaPro results for the sawmill operation

Label	Electricity	Combustion of natural gas	Heavy fuel oil	Diesel
Ozone depletion	39.9404	0.1088	11.6107	45.533
Global warming	20.5906	30.0018	4.1832	28.1083
Smog	10.8903	4.5936	1.8317	35.6167
Acidification	16.2673	3.155	9.0308	36.2707
Eutrophication	60.0788	0.4708	1.0767	33.379
Carcinogenics	35.2824	0.0647	0.5333	63.2736
Non carcinogenics	12.5748	0.0193	0.3403	86.9419
Respiratory effects	38.2276	0.4073	3.7919	34.5119
Ecotoxicity	59.8217	0.0534	0.6675	39.1295
Fossil fuel depletion	13.26	43.5055	5.1544	20.8224
Label	**Propane**	**Process steam**	**Combustion, dry wood residue**	
Ozone depletion	2.4394	0.3676	0	
Global warming	1.0262	14.4367	1.6532	
Smog	0.4138	5.3715	41.2826	
Acidification	0.4919	7.861	26.9232	
Eutrophication	0.355	0.7966	3.843	
Carcinogenics	0.6617	0.1843	0	
Non carcinogenics	0.0665	0.0572	0	
Respiratory effects	0.2722	1.5934	21.1958	
Ecotoxicity	0.2455	0.0823	0	
Fossil fuel depletion	1.0988	16.159	0	

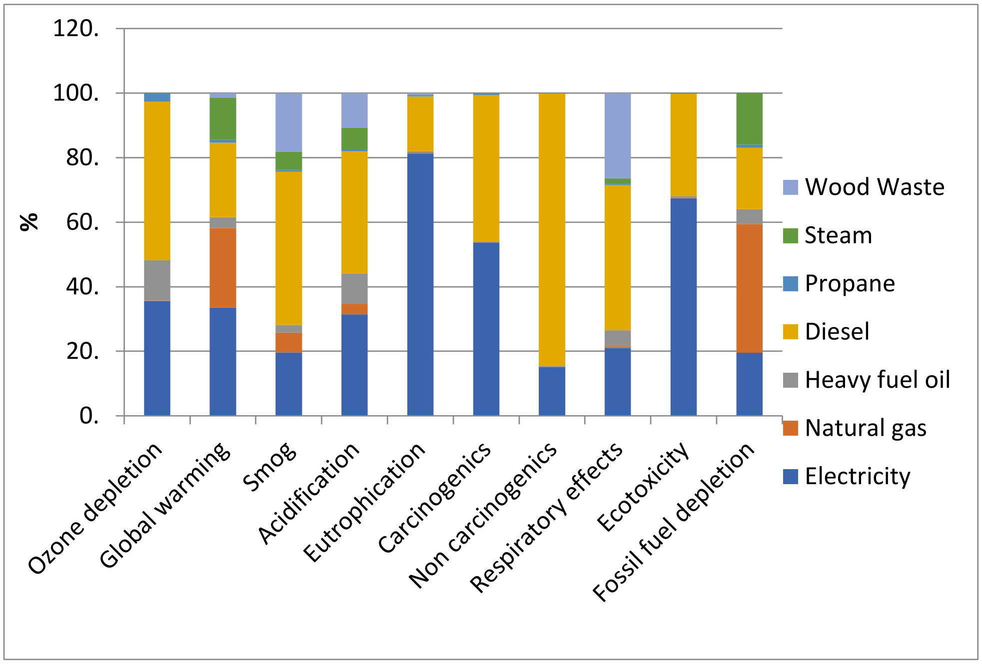

Figure 26 SimaPro results for sawmill operation unit

5.5 Pelletization

In production of wood pellets, a majority of environmental impacts - over 80% - can be attributed to electricity consumption in the pelletizing process. This consumption is driven by a variety of equipment, including the pellet mill, hammer mill, cooler, dryer motor, and other miscellaneous equipment. Of these, the drying process consumes the largest share of energy (Uasuf & Becker, 2011).

Pelletization is also a significant cost component in pellet production. However, it also incurs additional expenses due to wear and tear of rollers and dies, which leads to increased electricity consumption and maintenance costs. (Uasuf & Becker, 2011).

Table 8 SimaPro results for pelletization

Label	Electricity	Propane, burned in building machine	Diesel, burned in agricultural machinery	Combustion, dry wood residue
Ozone depletion	74.9719	3.5195	21.5086	0
Global warming	82.003	1.3109	11.756	4.93
Smog	17.666	0.3141	8.8533	73.1666
Acidification	38.6746	0.401	9.682	51.2425
Eutrophication	92.5832	0.13	4.0018	3.285
Carcinogenics	84.6296	0.4757	14.8947	0
Non carcinogenics	46.1587	0.1255	53.7157	0
Respiratory effects	29.3957	0.3148	13.0674	57.2222
Ecotoxicity	90.9245	0.1706	8.9048	0
Fossil fuel depletion	80.987	2.6389	16.374	0

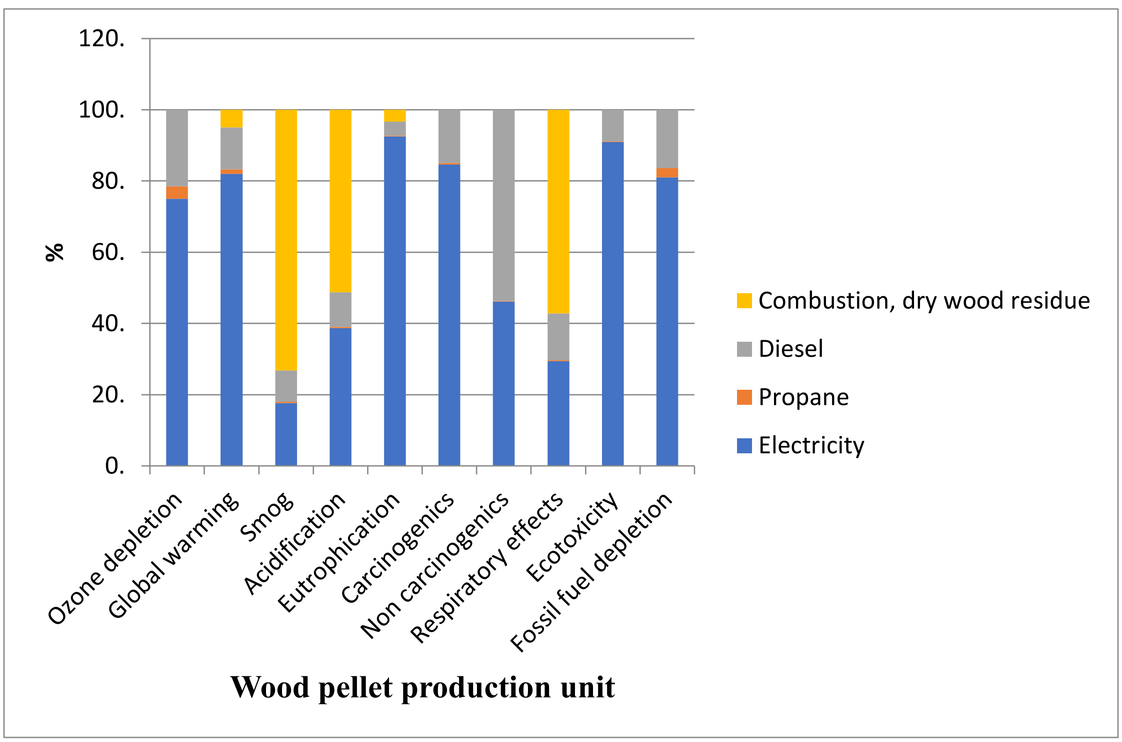

Figure 27 SimaPro results for pelletization

5.6 Comparative Analysis: Stages

LCA results presented in Figure 28 illustrate that pellet burning/combustion, and pellet production has a major share in environmental impacts of wood pellets. However, it should be noted that combustion of wood pellets is associated with few impact categories. Notably, the major impact categories affected by the combustion of wood pellets are smog, acidification, and respiratory effects.

Smog, and in particular particulate matters (PMs), could have adverse effects on human health, particularly on the respiratory system (Pa, 2010; Xing et al., 2016) and can pose a significant health risk.

Table 9 Sima pro results for all the stages

Label	forest management	transport	sawmill operation
Ozone depletion	18.328	22.8647	26.6599
Global warming	12.6955	13.4688	28.1657
Smog	7.3713	10.3863	14.9315
Acidification	8.3196	10.712	18.1469
Eutrophication	9.252	8.4207	29.6858
Carcinogenics	14.4804	10.1563	31.8504
Non carcinogenics	5.4161	11.6149	33.0591
Respiratory effects	2.6475	3.4117	7.7969
Ecotoxicity	10.1592	15.1652	30.2747
Fossil fuel depletion	17.5687	20.8075	28.7998
Label	**pellet production unit**	**wood pellet combustion**	
Ozone depletion	32.1474	0	
Global warming	36.1873	9.4828	
Smog	26.2243	41.0865	
Acidification	29.672	33.1494	
Eutrophication	45.3552	7.2864	
Carcinogenics	43.5129	0	
Non carcinogenics	49.9098	0	
Respiratory effects	13.0233	73.1206	
Ecotoxicity	44.4009	0	
Fossil fuel depletion	32.824	0	

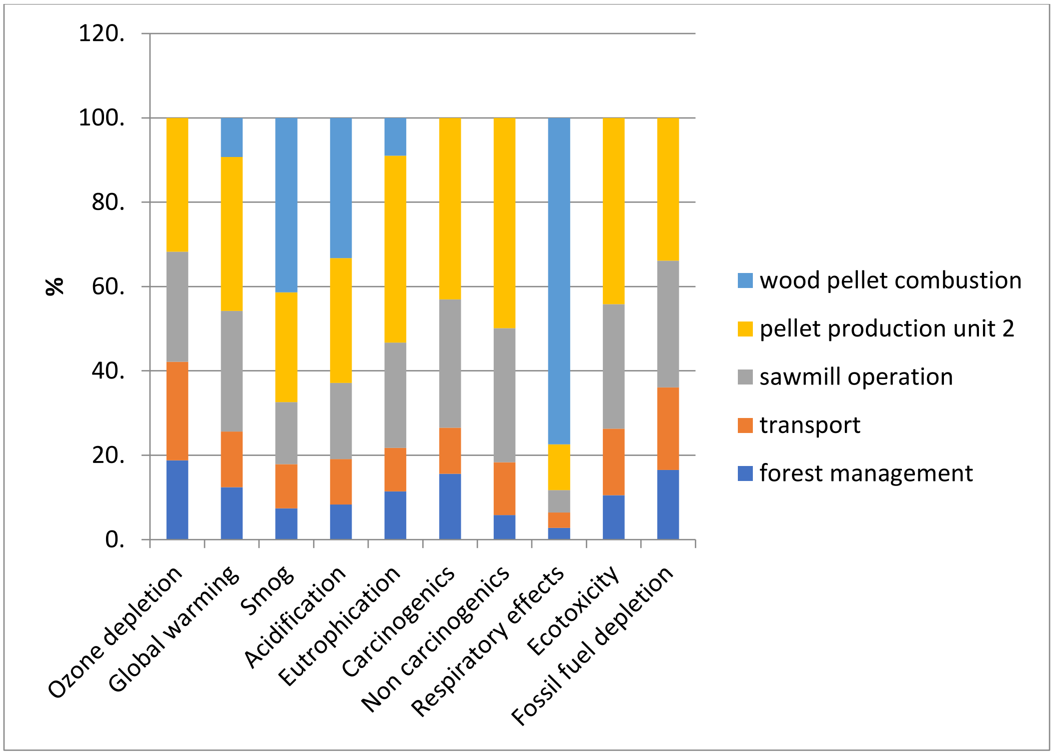

Figure 28 LCA across the stages

5.7 Comparative Analysis: Fuels

To estimate emissions from combustion of diesel, a calculation tool developed by Environmental Protection agency in the US is used (EPA, 2020) jointly with the methodologies proposed for quantifying GHG emissions in BC (Columbia, B., 2012). Data on emissions from wood pellet burning are obtained from Pa (2010) and (Government of Canada, 2018).

The results of comparing the environmental impacts and emissions associated with burning diesel and wood pellets are presented in Table 10.

Table 10 A comparison of emission contributions of wood pellets and diesel per unit of energy output

Substance Name	Wood pellet	Diesel	Unit
Carbon Monoxide (CO)	0.504009164	0.417743453	Kg/GJ
Sulphur Dioxide (SO_2)	0.011454754	0.130544829	Kg/GJ
Oxides of Nitrogen, expressed as NO2 (NO_x)	0.080183276	1.879845539	Kg/GJ
Volatile Organic Compounds (VOCs)	0.085910653	0.156653795	Kg/GJ
Total Particulate Matter (TPM)	0.068728522	0.130544829	Kg/GJ
Particulate Matter less than or equal to 10 µm (PM_{10})	0.063001145	0.130544829	Kg/GJ
Particulate Matter less than or equal to 2.5 µm ($PM_{2.5}$)	0.063001145	0.130544829	Kg/GJ
Bio CO_2	99.14089347	2.77	Kg/GJ
CO_2	---	67.43	Kg/GJ
CH_4	0.063573883	0.0035	Kg/GJ
N_2O	0.003321879	0.0104	Kg/GJ

Figure 29 illustrates the relative emission contributions, showing that wood pellets generally exhibit lower levels of most emissions, except for CH_4, CO, and bio-CO_2. The reason behind these findings is that the emissions of CO, CO_2, and CH_4 primarily result from the natural biodegradation and auto-oxidation processes of organic components found in wood (Yazdanpanah et al., 2014). It is important to note that in this study, the term "biogenic carbon dioxide emissions" refers specifically to emissions generated through the combustion, digestion, fermentation, or decomposition of materials derived from living organisms. This definition explicitly excludes fossil fuels, peat, and mineral carbon sources (US EPA, 2011).

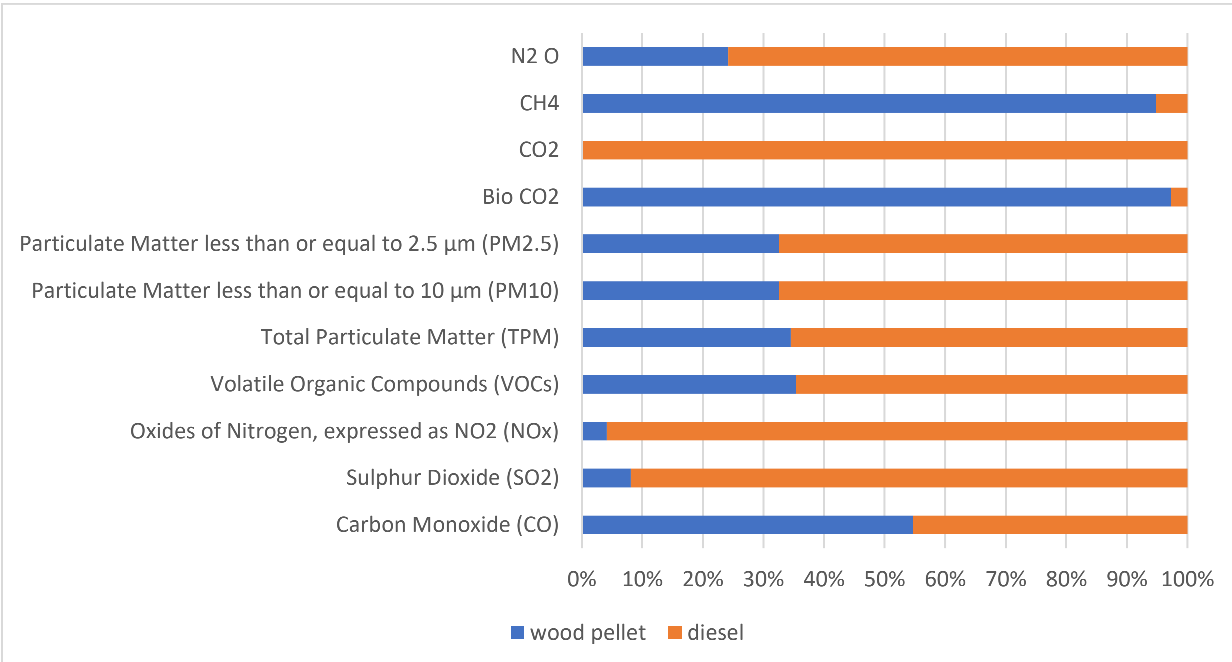

Figure 29 Relative emission contributions of wood pellet vs. diesel

According to SimaPro, pellets perform better in all midpoint impact categories, especially those that are non-carcinogenic.

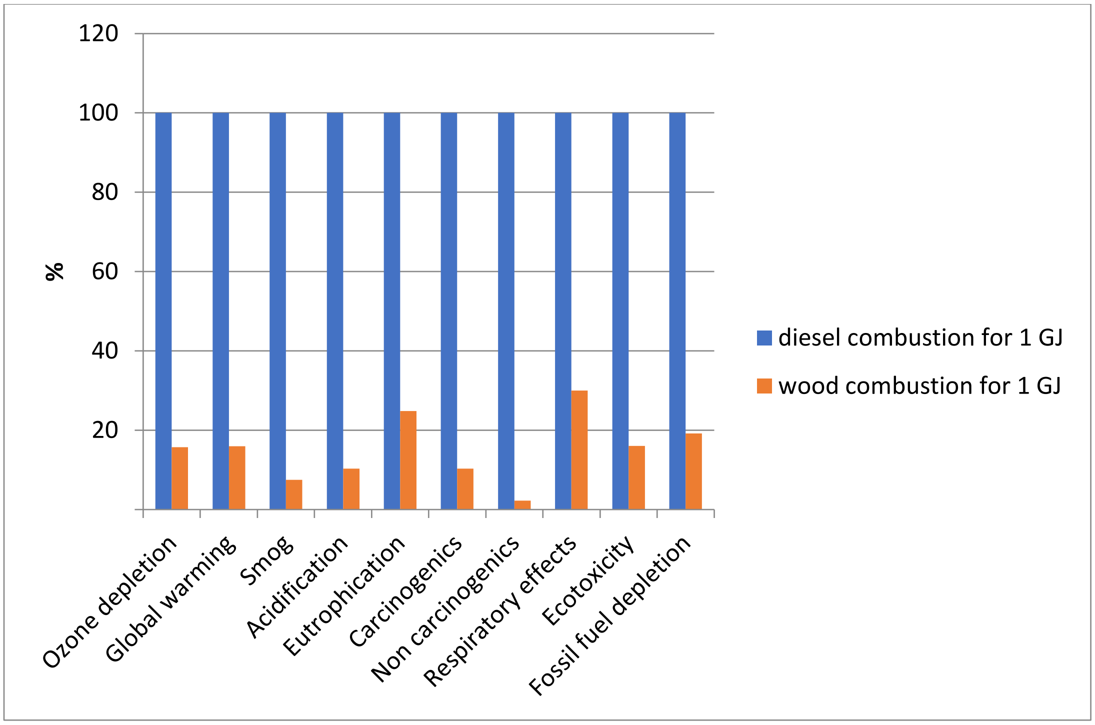

Figure 30 SimaPro results for comparison of wood pellet with diesel for 1 GJ of energy output

5.8 Discussion

This study involved a cradle-to-gate LCA for the utilization of wood pellets as an alternative fuel source for a case study remote community in Canada. The results indicated that the pelletization stage had a considerable share in most environmental impact categories, primarily due to the high electricity usage associated with its preparation and preprocessing. The production of wood pellets involves various processes such as drying, grinding, pelletizing, cooling, bagging, packaging machines, conveyors, and dust collectors, all of which are powered by electricity. The amount of electricity required varies depending on factors like production unit scale, raw materials, and processes employed. (Padilla-Rivera et al., 2017). As such, to minimize the environmental impact of pellet production, it is crucial to use renewable energy sources such as wind, solar, and hydropower. In addition, the production processes can be optimized to reduce energy consumption and waste, which can further minimize the environmental impact of pellet production. Wood pellet production can be optimized by investing in efficient equipment, fine-tuning process parameters, implementing effective waste management practices, installing heat recovery systems, utilizing renewable energy sources, and continuously monitoring and optimizing processes.

Although the pellet combustion stage may not contribute significantly to all impact categories, it can have a significant impact on the creation of smog and respiratory effects. To reduce these impacts, it is recommended to use high-quality wood pellets with low levels of impurities to reduce emissions. Installing a high-efficiency pellet stove or furnace can also maximize combustion and reduce emissions. Regular maintenance and cleaning of the stove or furnace can also ensure optimal performance and further reduce emissions. Proper ventilation and air circulation in the room can also minimize indoor air pollution. Burning pellets in moderation and avoiding overuse is also a means of minimizing overall environmental impact. By implementing these recommendations, the negative impacts of pellet combustion on the environment and human health could be mitigated.

In comparison to diesel, wood pellets were shown to perform better in many impact categories, particularly in non-carcinogenic categories. As such, wood-based bioenergy, particularly wood pellets, can be a sustainable alternative to fossil fuels and can provide reliable energy to remote communities. By financing wood-based bioenergy projects, the Canadian federal government can help reduce the reliance of rural communities on fossil fuels, promote sustainable energy systems, and stimulate economic growth and job creation.

In this study, the importance of domestic use of wood pellets was highlighted, by emphasizing considerable environmental and health consequences associated with ocean transportation when exporting Canadian wood pellets to other countries. Among these consequences are increased carbon dioxide emissions due to long-distance transportation, risks of marine pollution from shipping activities, and potential economic and social impacts on local communities. Although wood-based bioenergy has numerous advantages, such as reducing GHG emissions and encouraging sustainable forestry practices, its needed transport activities can cause adverse environmental effects. Therefore, it is crucial to meticulously assess and mitigate the impacts of transportation to ensure that wood-based bioenergy continues to be a sustainable and feasible alternative.

To corroborate the findings of this research, a comparison with a prior investigation conducted by Francesco et al. (2018) in Portugal, as a benchmark, was advocated. In their study, the LCA focused on both domestic and industrial production of wood pellets, taking into account differences in transportation distances, methodology selection, and data sets specific to each case study. Despite these variations, it was noted that the results of their study exhibited a similar pattern to the findings of this research. Specifically, particulate matter formation during the combustion stage of the LCA was identified as having significant respiratory effects in their study, which is also consistent with the findings of this study. Additionally, in their study, the largest proportion of impact related to forest stage and transportation was attributed to the ozone depletion impact category, which is in line with the findings of this research.

Chapter 6: Conclusions

This study employed LCA analysis to assess the environmental impact of utilizing wood pellets in Kwadacha, a remote community in BC, Canada. The research emphasizes the importance of considering electricity consumption associated with the machinery used in the compression and drying stages of pelletization, as well as the respiratory impacts resulting from pellet combustion. Notably, the study identified significant respiratory impacts from pellet combustion. Therefore, it is necessary to adopt mitigation strategies during the pelletization phase to minimize the environmental impacts. Moreover, the findings underscore the need to reduce energy consumption during pelletization and transition to renewable energy sources for the electricity required in pellet preparation and preprocessing. The transportation phase, involving long-distance transportation to the final destination, was also recognized as a significant contributor to environmental impacts throughout various stages of wood pellet production. Despite the identified impacts, the results indicate that the use of wood pellets generally results in lower environmental impacts compared to fossil fuels across most impact categories.

6.1 Limitations

There are several limitations in this study that should be taken into consideration when interpreting the results. Data availability for all LCA stages was one of the main limitations. Furthermore, this study was limited by the pre-determined system boundaries, especially in terms of transportation means and distances. Due to a lack of information on other operational pellet production units that could transport wood pellets to the remote community, a major pellet production unit in BC, was assumed as the supplier.

Since data availability was one of the main limitations, efforts should be made to improve data collection for all stages of the LCA. This could involve gathering more accurate and detailed data on harvesting, transportation, sawmill operation, pellet production, and combustion stages. Collaborating with local stakeholders and industry experts in the remote Canadian community could help in obtaining relevant data.

Given that the pre-determined system boundaries had limitations, it would be beneficial to reassess and refine the boundaries to capture a more comprehensive and accurate picture of the environmental impacts. This could involve considering additional factors such as the transportation means and distances for other operational pellet production units. Obtaining specific information on transportation distances and modes relevant to the remote community would help provide a more realistic assessment.

Since the study assumed a major pellet production unit in BC as the supplier, it may be valuable to incorporate regional variations in the analysis. Different regions may have varying transportation distances, infrastructure, and production methods, which can significantly impact the environmental impacts associated with wood pellet production and transportation. Including data from different regions or conducting case studies in multiple remote Canadian communities could provide a more comprehensive understanding of the variations and their implications.

6.2 Future Work

This section outlines the potential directions for further research and development based on the findings from the current study, as well as the limitations of the study. The purpose of this section is to identify areas of development and questions that remain unanswered, and then chart a course towards gaining a deeper understanding of the subject.

Refine the LCA: Consider conducting a more comprehensive refinement of the LCA by gathering additional data and enhancing the analysis. This process could involve incorporating more detailed information regarding the transportation and combustion stages to provide a more precise evaluation of their environmental impacts. Furthermore, it is beneficial to incorporate sensitivity analysis or uncertainty assessment to quantify the robustness of the results, ensuring a more reliable and comprehensive LCA study.

Assess the economic feasibility: Alongside the environmental analysis, it is crucial to assess the economic feasibility of adopting wood pellets as an alternative to diesel generators. This evaluation should encompass various factors, including infrastructure development costs, pellet production expenses, transportation expenditures, and ongoing maintenance requirements. Additionally, it is important to consider the social and economic factors specific to the remote communities, such as job creation, local economic development, and the potential social acceptance of wood pellet systems. Furthermore, examining potential long-term fuel cost savings can provide a comprehensive understanding of the economic viability of wood pellet utilization.

Consider other renewable energy alternatives: While wood pellets have demonstrated promising results as an alternative to diesel, it is important to explore additional renewable energy options that could be suitable for remote communities. This exploration could involve considering technologies such as solar power, wind turbines, and hydroelectricity. Each option has its own specific advantages and drawbacks that should be evaluated for informed decision-making. For instance, solar power offers clean energy generation and is particularly suitable for regions with abundant sunlight. Wind turbines harness the power of wind, but their effectiveness can be dependent on wind availability. Hydroelectricity utilizes flowing water to generate electricity but may require significant infrastructure and environmental considerations. By assessing the potential benefits and drawbacks of these alternative renewable energy sources, a more comprehensive overview can be obtained to guide decision-making in remote communities.

Engage with the community: It is crucial to involve the local community and stakeholders in the decision-making process. Conduct consultations and workshops to gather their input, address any concerns or preferences, and educate them about the potential benefits of transitioning to sustainable energy sources. This engagement will help ensure a smooth transition and foster community support.

Conduct pilot projects: Consider implementing small-scale pilot projects in selected remote communities to test the practicality and efficiency of using wood pellets or other renewable energy sources. Monitor and evaluate the performance of these systems over an extended period, collecting data on energy generation, emissions, and overall community satisfaction.

Long-term monitoring and assessment: Once renewable energy systems are implemented, it is essential to prioritize long-term monitoring and assessment. This continuous evaluation serves several purposes, including the identification of challenges, the assessment of the effectiveness of the transition, and the generation of insights for ongoing improvements and optimization. Moreover, it is crucial to emphasize the significance of knowledge-sharing and collaboration with other remote communities that have implemented similar energy systems. This facilitates the exchange of best practice, enabling a collective learning process and fostering continuous improvement in the remote community's renewable energy initiatives.

Exploring the potential of torrefied wood pellets: Torrefied wood pellets present both advantages and challenges compared to conventional wood pellets. They exhibit significantly higher emissions during production due to the energy-intensive thermal treatment process involved. However, torrefied pellets demonstrate lower emissions in terms of end use and transportation when considering the entire lifecycle. Torrefaction enhances the calorific value of the feedstock, resulting in increased energy density in pellets. Nevertheless, using torrefied wood pellets comes with challenges such as additional energy and cost requirements, variations in end-product quality, limitations in particle size, control difficulties in the reactor, safety concerns, technical accommodations in manufacturing facilities, and potential impact on die life and lubrication. The market for torrefied wood pellets in Canada is limited, mainly due to higher prices. Further research and development are needed to address these challenges and unlock the full potential of torrefied wood pellets for remote communities.

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