energies

MDPI

Article

Life Cycle Assessment of Bioenergy Production Using Wood Pellets: A Case Study of Remote Communities in Canada

Saghar Sadaghiani [1], Fereshteh Mafakheri [2,*] and Zhi Chen [1]

[1] Department of Building, Civil and Environmental Engineering, Concordia University, Montreal, QC H3G 1M8, Canada; saghar.sadaghiani@gmail.com (S.S.); zhi.chen@concordia.ca (Z.C.)
[2] Ecole Nationale D'administration Publique (ENAP), Université du Québec, Montréal, QC H2T 2C8, Canada
* Correspondence: fereshteh.mafakheri@enap.ca

Abstract: In remote communities of Canada, diesel is the primary source of electricity and heat. Promoting sustainable and diverse means of heat and power generation is essential to providing reliable and less carbon-intensive energy supply to remote communities. Among renewable energy sources in Canada, biomass is a major source of energy, with wood pellets being a notable contributor. In this study, using wood pellets in a remote community of Canada is investigated using life cycle analysis (LCA). Furthermore, wood pellet combustion is compared with diesel combustion, the most common fossil fuel in these regions. SimaPro (version 8.4.0.0) was used with Ecoinvent 3 as the primary library because of the nature of the feedstock. Harvesting, transportation, sawmill operation, pelletization, and combustion stages are considered in LCA. In doing so, first, life cycle data related to each of these stages are collected with respect to eight impact categories of global warming, ozone depletion, carcinogenic, non-carcinogenic, smog, respiratory effects, acidification, eutrophication, ecotoxicity, and fossil fuel depletion. The results indicate that pelletization and combustion stages have the greatest environmental impact, specifically in terms of non-carcinogenic effects from pelletization and respiratory effects from pellet combustion. Additionally, when comparing wood pellets to diesel, wood pellet combustion exhibits superior performance across various impact categories, particularly in non-carcinogenic effects.

Keywords: remote communities; wood pellets; diesel; sustainable energy; life cycle analysis (LCA); renewable energy sources

Citation: Sadaghiani, S.; Mafakheri, F.; Chen, Z. Life Cycle Assessment of Bioenergy Production Using Wood Pellets: A Case Study of Remote Communities in Canada. *Energies* **2023**, *16*, 5697. https://doi.org/10.3390/en16155697

Academic Editor: Fernando Rubiera González

Received: 3 July 2023
Revised: 23 July 2023
Accepted: 28 July 2023
Published: 30 July 2023

1. Introduction

Greenhouse gas (GHG) emissions are contributing to global warming and climate change, affecting human and ecosystem health, as well as security of food and water supplies [1]. 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 [2]. Promoting renewable energy has emerged as a solution to offset GHG emissions [3]. There was a total supply of 12,795 petajoules (PJ) of energy in Canada, of which over 75% came from fossil fuels [4]. A total of 2067 PJ of energy is generated by renewable sources, of which 566 PJ comes from bioenergy. Over the past few years, natural gas consumption has increased in Canada, mainly replacing other fossil fuels such as coal and diesel, while renewable energy supply has remained relatively stable (between 16% and 18%) [4].

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 [5]. Additionally, Canada is investing in smart grids to facilitate access to clean electricity from neighbouring provinces and implementing a carbon pollution pricing system that will hold the electricity industry accountable for reducing emissions [5].

The extreme weather condition in remote communities of Canada makes energy supplies vital to the survival of these regions as well as to 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 (e.g., 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 [6]. Fossil fuel dependence and such a lack of diversity in energy sources limits economic, environmental, and social development of these communities [7]. 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. In addition, using bioenergy instead of traditional fossil fuels has the potential to reduce GHG emissions and consumption of non-renewable resources [8]. 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 [6]. 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 [9]. Compressed wood fiber biofuels, known as wood pellets, have become popular for household heating [10].

With 6.5% of the world's bioenergy potential and 9% of the world's forests, Canada produces the highest amount of biomass per capita in the world [11]. Canada is also the world's third-largest timber exporter. About 90% of wood pellets manufactured in Canada are exported to Asia, Europe, and the United States [3]. The European Union and Southeast Asia are expected to import more wood pellets by 2030 as their primary feedstock in co-firing power plants [12]. Studies using life cycle analysis (LCA) show that shipping a tonne of wood pellets to Europe consumes approximately 7.2 GJ, which is equivalent to about 39% of the pellets' total energy. In addition, ocean transportation is associated with significant environmental and health impacts, including air pollution, GHG emissions, oil spills, etc. [13].

In the light of the above facts, this study aims to assess the environmental impacts of using wood pellets as an alternative to fossil fuels as well as a means of transition towards other renewable energies, such as solar and wind. Specifically, this study focuses on the use of domestic wood pellets in Canada, particularly in remote regions in need of diversifying energy sources, as exporting wood pellets is associated with adverse environmental effects. While many studies have compared the environmental impact of wood pellets to that of coal or natural gas, the aim will be to compare the use of wood pellets to diesel, which is commonly used in remote communities of Canada.

This study focuses on remote communities in British Columbia (BC), which holds 45% of Canada's pellet mill capacity. BC wood pellets are primarily sourced from saw milling residuals, forestry and agriculture residues, and low-quality logs [14]. The objective is to examine the environmental impacts of wood pellets through an LCA, from harvesting to combustion in BC remote communities. A comparison will be made between the combustion impacts of wood pellets and diesel to evaluate the potential as a cleaner alternative. The paper's structure includes a discussion of the case study's significance (Section 2), a detailed presentation of the LCA methodology (Section 3), results analysis (Section 4), discussions on research value with future research directions (Section 5), and concluding remarks.

2. Case Study Description

In Canada, the majority of pellets are made from forestry residues, industrial waste, sawmills, and wood production enterprises. Timber harvest wastes are another source of biomass for wood pellet manufacturing. A small percentage of wood pellet production is used for domestic heating and electricity generation in Canada (about 100,000 to 200,000 tonnes). The vast majority of this fuel is exported [15]. BC is considered one of the world's largest producers of wood pellets, exporting 99% of its 2.5 million tonnes per year [16].

Although various studies have demonstrated that wood pellets offer better economic efficiency in Canada compared to fossil fuels [3,17], one of the main challenges faced by the biomass industry is that pellet boilers have not been used widely in Canada. At the moment, Canada does not manufacture such boilers and does not import them [3]. This has served as the main barrier to domestic use of Canadian pellets. In contrast, Canada benefits economically from exporting its wood pellets [17]. As such, wood pellets have a very small share of energy sources in Canada [3]. To address the above challenges, the Wood Pellet Association of Canada (WPAC) is tasked with facilitating the import of European-manufactured pellet boilers to Canada with adoptions so far in Prince Edward Island and Ontario. The industry still faces obstacles in acquiring and using modern wood pellet boilers [3].

In this study, the aim is to demonstrate a case study on how Canada can benefit from using wood pellets as a renewable energy source to replace fossil fuels. By using wood pellets, Canadian rural areas would benefit from lower heating costs and reduced GHG emissions, as well as creating new jobs [18]. In particular, this study explores the potential of wood pellets as a sustainable energy source in remote communities. 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 [19].

Our study specifically focuses on the Kwadacha First Nation, a remote community located in Fort Ware, BC. This community, situated approximately 570 km north of Prince George, is only accessible by logging roads or air transportation [20]. 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. The map of Northern British Columbia communities is presented in Figure 1, with the above mentioned communities circled in red line. Rural Practice Subsidiary Agreement (RSA) practiced in BC assesses the communities using a number of criteria to classify them based on their level of isolation/remoteness. Based on the overall points earned according to these criteria the communities are classified into A, B, C, and D categories (where A represents the highest level of isolation).

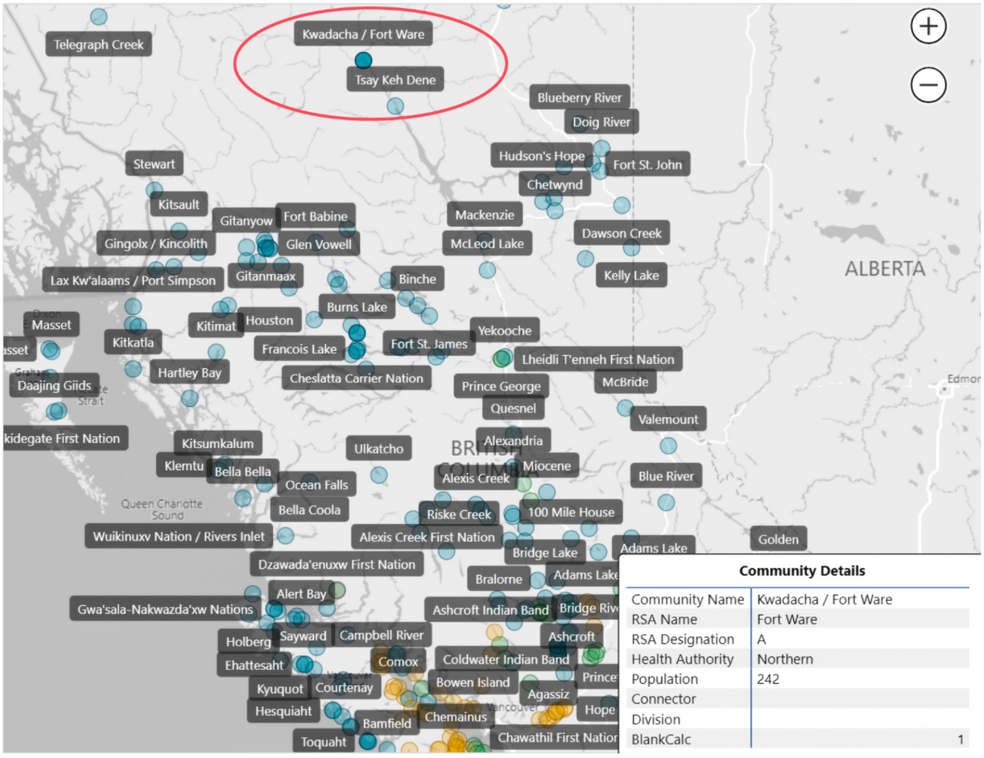

Figure 1. Map of rural communities in northern British Columbia, Canada [21].

3. Methodology

The International Organization for Standardization (ISO) has developed several standards related to LCA to promote consistent and credible environmental assessments [22]. 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 [23].

The LCA is a method for assessing how products and decisions impact the environment [24]. Using LCA can be beneficial, as it could provide information about potential environmental impacts of a product before it is marketed, which can help prevent such adverse impacts. The steps of the LCA are described in the following sub-sections [25–27]:

(1) Goal and scope definition: The study's goal and scope are defined before collecting any data. The 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 [25].
(2) Life cycle inventory analysis (LCI): The data collection process for an LCA starts after the demarcation lines are set. During the LCI stage, the inputs and outputs of an industrial system are quantified and documented, considering the specified functional unit [26].
(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 [26].
(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 [27].

3.1. System Boundary Description

Figure 2 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 1 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.

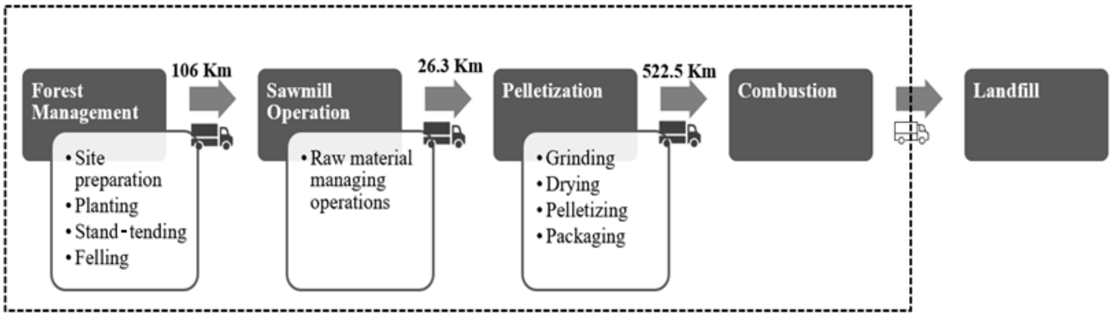

Figure 2. LCA system boundary.

More than 60% of BC's land is covered by forest, and less than one-third of 1% of BC's forests are logged annually. For logging purposes, no land is generally converted into forests [28]. Therefore, land use changes are not considerable. Also, this study does not take into account how logging practices may affect biodiversity. By excluding the end-of-life disposal phase, the LCA will also not 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.

3.2. 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 software platforms and databases (such as SimaPro) exist that offer a wealth of secondary data [29], some materials or processes might still be missing.

Within the realm of LCA data, it is useful to distinguish between two types of data: primary data, which are self-generated through surveys, interviews, and experiments, and secondary data, which are stored as part of an organization's records and can be extracted from various data files [30]. In this study, secondary data were primarily used from sources such as literature, surveys, online databases, and SimaPro's Ecoinvent database [29]. 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 the largest and most consistent LCI database that supports data transparency [29].

3.2.1. 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 [31] notes that spruce and pine are among the most common tree species in Canada for producing wood pellets, which are the focus of this study. The data for these tree species were obtained from the Ecoinvent database using SimaPro software version 8.4.0.0 [29]. 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.

3.2.2. LCI Parameters for Transportation

The LCI parameters that are associated with the 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, and payload capacity that contribute to the environmental impacts of pellet transportation.

We studied different transportation options and distances for delivering the feedstock, considering guidelines from the Government of Canada [32] and research on LCA models and methods used for shipping wood pellets from Canada to Europe [13]. Based on the references, trucks are the best choice for transportation when there is no access to waterways, and the distance between the source of the materials and the production facility is assumed to be 100 km. It is important to mention that wood pellet facilities are often situated close to forestry harvest operations and sawmills. This proximity has two advantages: shorter transportation distances are not only economically beneficial but also lead to improved sustainability of biofuels by reducing environmental impacts associated with transport [32]. According to Pa et al. (2013) and Magelli et al. (2009) [28,33], the distance from the sawmill to the pellet production units is estimated to be about 26.3 km.

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. Premium Pellet has a production capacity of up to 170,000 metric tonnes of pellets. It is mainly a supplier to the power industry in BC to replace coal in electricity generation. It also serves customers for residential heating in BC [34]. 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.

3.2.3. 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, water 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) [35] 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. These data included energy consumption per tonne of pellets, reported in MJ, and emissions per tonne of pellets, reported in Kg. This information is an essential component in assessing the environmental impact of the wood pellet production process and identifying areas for improvement.

3.3. Impact Assessment

SimaPro provides several impact assessment methods for calculating impact assessment findings [29]. 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 such as ozone depletion, global warming, acidification, eutrophication, tropospheric ozone (smog), ecotoxicity, human health-related effects, human health cancer effects, human health non-cancer, fossil fuel depletion, and land-use effects [36]. 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.

4. 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 [29] with the objectives of:

1. Assessing the environmental impact of wood pellets 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.

4.1. Harvesting and Forest Management

Energy-wood 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 [37]. 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 the construction of roads, logging, and transportation with impacts on the environment [38]. The results obtained from SimaPro for harvesting and forest management phase are summarized in Figure 3.

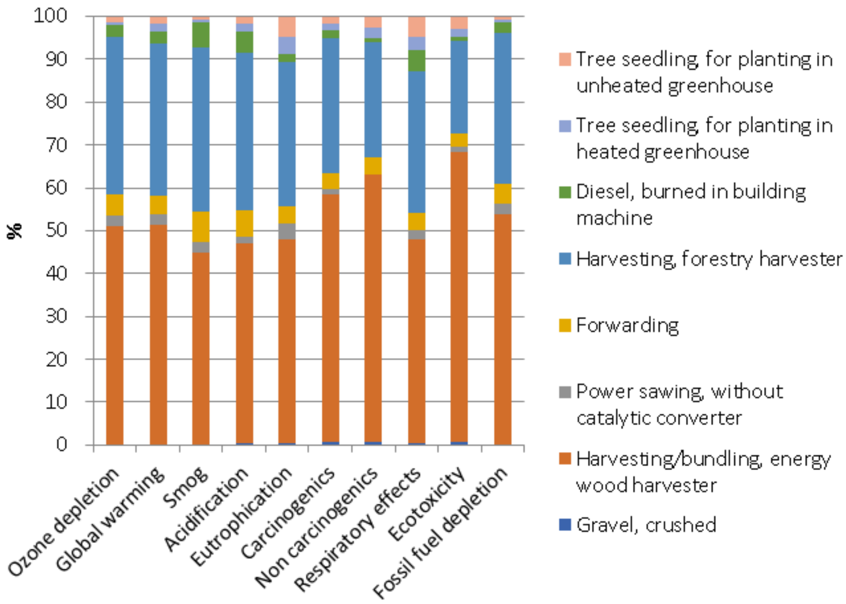

Figure 3. SimaPro results for harvesting and forest management [29].

4.2. Transportation

The LCA results presented in Figure 4 indicate that the transportation of wood pellets to remote communities is the primary contributor to the environmental impacts of wood pellets. This is primarily due to the considerable distance between the pellet production facility and these remote areas. Transportation of feedstock 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.

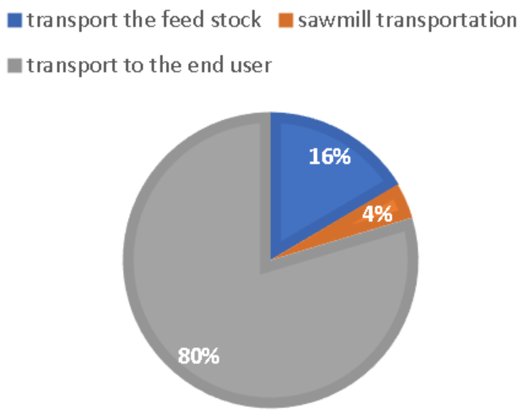

Figure 4. The transportation scenarios considered in the LCA of wood pellets.

4.3. 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, the environmental impact of diesel usage should be carefully considered when selecting a power source option for sawmill operations [39].

Operations of a hardwood sawmill involve log debarking, log sawing, flitch edging, trimming, side-cut 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 is being used [40]. The results obtained from SimaPro for the sawmill phase are presented in Figure 5.

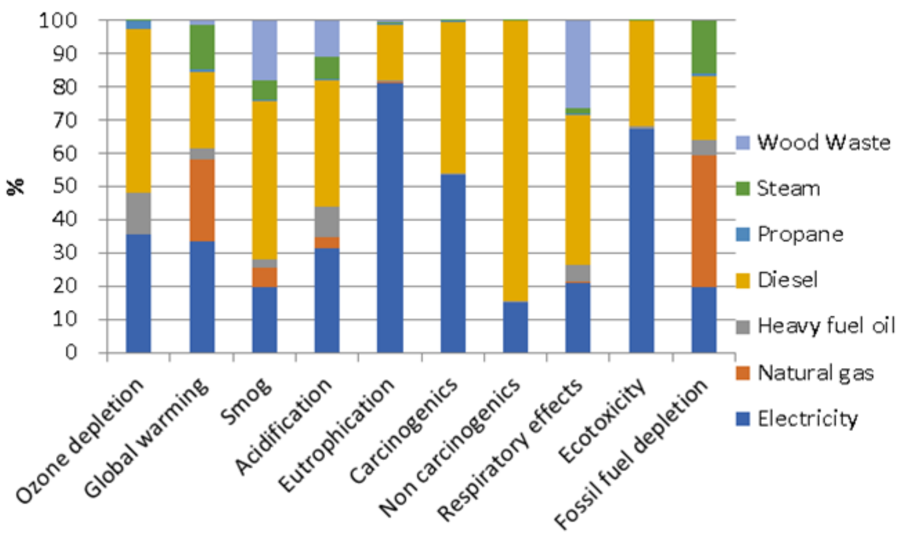

Figure 5. SimaPro results for sawmill operation unit [29].

4.4. Pelletization

In the 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 [41].

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 [41]. Figure 6 shows the results obtained from SimaPro for the pelletization phase.

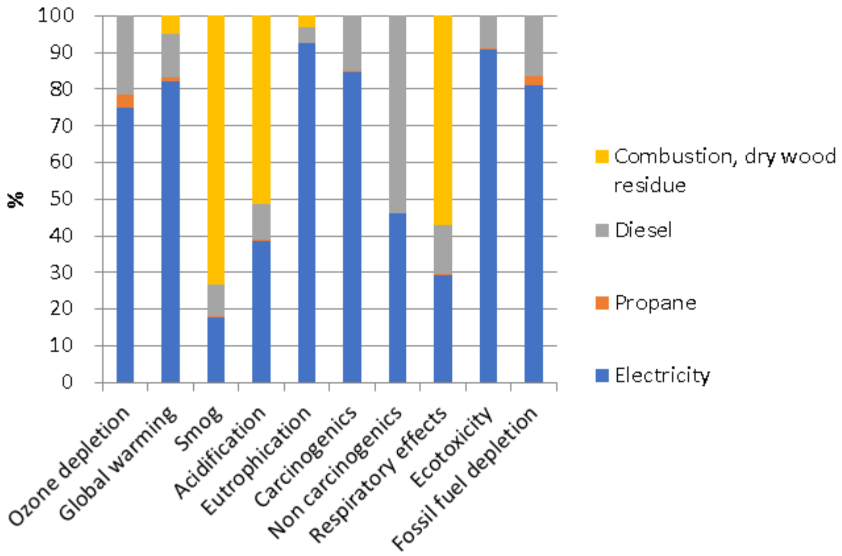

Figure 6. SimaPro results for pelletization [29].

4.5. Comparative Analysis: Stages

LCA results presented in Figure 7 illustrate that pellet burning/combustion and pellet production have a major share in environmental impacts of wood pellets. However, it should be noted that the combustion of wood pellets is associated with several 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 [35,42] and can pose a significant health risk.

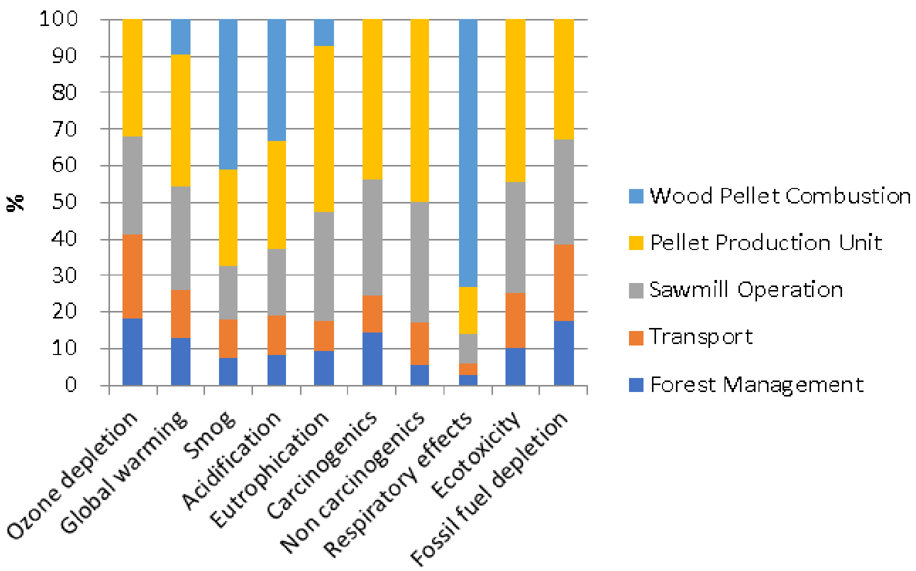

Figure 7. LCA across the stages [29].

4.6. Comparative Analysis: Fuels

To estimate emissions from the combustion of diesel, a calculation tool developed by the Environmental Protection Agency in the US is used [43] jointly with the methodologies proposed for quantifying GHG emissions in BC [44]. Data on emissions from wood pellet burning are obtained from Pa (2010) and the Government of Canada (2018) [35,45].

The results of comparing the environmental impacts and emissions associated with burning diesel and wood pellets are presented in Table 1.

Table 1. Emission contributions of wood pellets and diesel combustion per unit of energy output (kg/GJ).

Substance	Wood Pellet (kg/GJ)	Diesel (kg/GJ)
Carbon Monoxide (CO)	0.504009164	0.417743453
Sulphur Dioxide (SO_2)	0.011454754	0.130544829
Oxides of Nitrogen, expressed as NO_2 (NO_x)	0.080183276	1.879845539
Volatile Organic Compounds (VOCs)	0.085910653	0.156653795
Total Particulate Matter (TPM)	0.068728522	0.130544829
Particulate Matter $\leq$ 10 µm (PM_{10})	0.063001145	0.130544829
Particulate Matter $\leq$ 2.5 µm ($PM_{2.5}$)	0.063001145	0.130544829
Bio CO_2	99.14089347	2.77
CO_2	---	67.43
CH_4	0.063573883	0.0035
N_2O	0.003321879	0.0104

The table demonstrates that wood pellets emit lower levels of most emissions, with the exception of CH_4, CO, and bio-CO_2. The rationale behind these numbers is that the emissions of CO, CO_2, and CH_4 are mainly due to natural biodegradation and auto-oxidation of organic components present in wood [46]. In this study, biogenic carbon dioxide emissions are specifically defined as those resulting from the combustion, digestion, fermentation, or decomposition of biologically derived materials, excluding fossil fuels, peat, and mineral carbon sources [47].

According to SimaPro, pellets perform better in all midpoint impact categories, especially those that are non-carcinogenic. The results from SimaPro for comparing pellets and diesel are summarized in Figure 8.

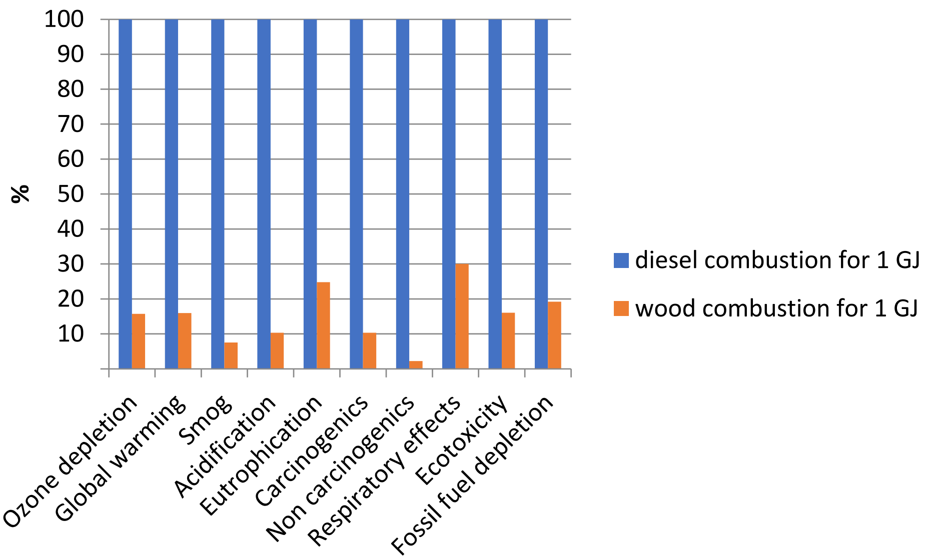

Figure 8. SimaPro results for comparison of wood pellet with diesel for 1 GJ of energy output.

5. Discussion

This study involved a cradle-to-gate LCA for 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 [48]. 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.

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 reliance of rural communities on fossil fuels, promote sustainable energy systems, and stimulate economic growth and job creation.

In this study, the importance of the 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. Although wood-based bioenergy has numerous advantages, such as reducing GHG emissions and encouraging sustainable forestry practices, its required 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 [49].

In order to corroborate the findings of this research, a comparison with a prior investigation conducted by Francesco et al. (2018) [50] in Portugal, as a benchmark, was advocated. The LCAs of both domestic and industrial production of wood pellets were targeted, accounting for variations in transportation distances, methodology selection, and differing data sets based on each case study. Despite these dissimilarities, it was observed that their results exhibited a comparable pattern to this study. 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 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 findings of this research.

6. Conclusions

To evaluate the environmental impact of utilizing wood pellets for Kwadacha, a remote community in BC, Canada, this study utilized LCA. The research highlights the significance of electricity consumption linked with the machinery utilized in the compression and drying stages of pelletization, and the respiratory impacts linked with pellet combustion. Therefore, to minimize the mentioned environmental impacts of pelletization, mitigation strategies should be adopted during this phase. In addition, the results pointed to the need to decrease the energy consumption during pelletization and shifting to renewable energy sources to supply electricity needed during preparation and preprocessing of the pellets. Additionally, the transportation phase, which involves long-distance transportation to the final destination, was recognized as a significant factor contributing to environmental impacts in various stages of wood pellet production. Furthermore, despite all of the above identified impacts, the results indicated that using wood pellets was still associated with lower environmental impacts in comparison with fossil fuels in most categories of impact.

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, one of the major pellet production units in BC was assumed as the supplier. Consequently, the transportation distance between the pellet production unit and the remote community was long, contributing to a high level of related environmental impacts.

To address the above limitations, future work should focus on conducting small-scale pilot projects in selected remote communities to use wood pellets as an alternative energy source and test the ways to improve the efficiency of the process. Long-term monitoring and assessment of these implemented systems could provide valuable insights into their performance, challenges, and impacts over time, and can serve as source of data for future LCA studies. Additionally, investigating the potential of torrefied wood pellets and addressing challenges such as higher emissions and energy requirements, as well as cost considerations will contribute to unlocking their full potential as a sustainable energy option for remote communities [51], necessitating further research and development efforts.

Author Contributions: Conceptualization, F.M. and Z.C.; Methodology, S.S.; Software, S.S.; Validation, S.S. and F.M.; Formal analysis, S.S. and Z.C.; Investigation, S.S., F.M. and Z.C.; Resources, F.M. and Z.C.; Writing—original draft preparation, S.S.; Writing—review & editing, F.M. and Z.C.; Supervision, F.M. and Z.C.; Project administration, F.M.; Funding acquisition, F.M. and Z.C. All authors have read and agreed to the published version of the manuscript.

Funding: This study was funded through a Discovery grant from the Natural Sciences and Engineering Research Council of Canada (NSERC), Grant No. RGPIN-2019-07086.

Data Availability Statement: The research data used in this article will be made available upon request from the corresponding author.

Acknowledgments: The authors are thankful to the editor and three anonymous reviewers for their valuable comments and suggestions that were very helpful in improving the quality of this manuscript.

Conflicts of Interest: The authors declare that there are no relevant financial or non-financial competing interest to report.

References

1. Cambero, C.; Hans Alexandre, M.; Sowlati, T. Life cycle greenhouse gas analysis of bioenergy generation alternatives using forest and wood residues in remote locations: A case study in British Columbia, Canada. *Resour. Conserv. Recycl.* **2015**, *105*, 59–72. [CrossRef]
2. NRCAN. Government of Canada. Natural Resources Canada. 17 August 2022. Available online: https://www.nrcan.gc.ca/energy-efficiency/green-buildings/24572 (accessed on 25 November 2022).
3. Cools, E. A Perfect Match: European Boilers and Canadian Wood Pellets. Canadian Biomass Magazine. 2 August 2022. Available online: https://www.canadianbiomassmagazine.ca/a-perfect-match-european-boilers-and-canadian-wood-pellets/#:~:text=Fuel%20poverty%20in%20Canada%20is%20on%20the%20rise&text=Today%2C%20because%20the%20Canadian%20wood,Europe%20and%20the%20United%20States (accessed on 21 October 2022).
4. Vanderfleet, O.; Klain, A.; Gagnon, B. *Implementation of Bioenergy in Canada—2021 Update*; IEA Bioenergy: Paris, France, 2021; pp. 1–7.
5. Government of Canada. Canada.ca. 24 October 2019. Available online: https://www.canada.ca/en/environment-climate-change/services/managing-pollution/energy-production/electricity-generation.html (accessed on 28 March 2023).
6. Mafakheri, F.; Adebanjo, D.; Genus, A. Coordinating biomass supply chains for remote communities: A comparative analysis of non-cooperative and cooperative scenarios. *Int. J. Prod. Res.* **2020**, *59*, 4615–4632. [CrossRef]

7. Khoddami, S.; Mafakheri, F.; Zeng, Y. A system dynamics approach to comparative analysis of Biomass Supply Chain Coordination Strategies. *Energies* **2021**, *14*, 2808. [CrossRef]
8. McKechnie, J.; Saville, B.; MacLean, H.L. Steam-treated wood pellets: Environmental and financial implications relative to fossil fuels and conventional pellets for electricity generation. *Appl. Energy* **2016**, *180*, 637–649. [CrossRef]
9. Dias, G.M.; Ayer, N.W.; Kariyapperuma, K.; Thevathasan, N.; Gordon, A.; Sidders, D.; Johannesson, G.H. Life cycle assessment of thermal energy production from short-rotation willow biomass in southern Ontario, Canada. *Appl. Energy* **2017**, *204*, 343–352. [CrossRef]
10. Laschi, A.; Marchi, E.; González-García, S. Environmental performance of wood pellets' production through life cycle analysis. *Energy* **2016**, *103*, 469–480. [CrossRef]
11. Buss, J.; Mansuy, N.; Madrali, S. De-Risking Wood-based Bioenergy Development in remote and indigenous communities in Canada. *Energies* **2021**, *14*, 2603. [CrossRef]
12. Dafnomilis, I.; Lodewijks, G.; Junginger, M.; Schott, D.L. Evaluation of wood pellet handling in import terminals. *Biomass Bioenergy* **2018**, *117*, 10–23. [CrossRef]
13. Magelli, F.; Boucher, K.; Bi, H.T.; Melin, S.; Bonoli, A. An environmental impact assessment of exported wood pellets from Canada to Europe. *Biomass Bioenergy* **2009**, *33*, 434–441. [CrossRef]
14. Naturallywood. What are Wood Pellets and How are They Made? 30 June 2021. Available online: https://www.naturallywood.com/products/wood-pellets/ (accessed on 28 November 2021).
15. NRCAN. Wood Pellets. Natural Resources Canada. Available online: https://natural-resources.canada.ca/our-natural-resources/forests-forestry/forest-industry-trade/forest-products-applications/wood-pellets/13736 (accessed on 16 July 2020).
16. Watson, B.B.C. Trees are b eing tur ned into wo od pe llets-and th at's ba d for the cli mate and wor kforce, cri tics say | CBC news. CBCnews. 8 April 2021. Available online: https://www.cbc.ca/news/canada/british-columbia/ccpa-report-wood-pellets-1.5979498#:~:text=In%20a%202020%20article%20published2.5%20million%20tonnes%20that%20year (accessed on 24 August 2022).
17. Yan, C.; Rousse, D.; Glaus, M. Multi-criteria decision analysis ranking alternative heating systems for remote communities in Nunavik. *J. Clean. Prod.* **2019**, *208*, 1488–1497. [CrossRef]
18. Jiggens, M. Residential u Se of Wo od Pelle ts: A Mis sed Opport Unity in Canada. Canadian Biomass Magazine. 2 August 2022. Available online: https://www.canadianbiomassmagazine.ca/residential-use-of-wood-pellets-a-missed-opportunity-in-canada/ (accessed on 3 November 2022).
19. Madrali, S.; Blair, J. Remotely po werful: Nine r ural comm unities' exper ience with Bioenergy—Part 1. Canadian Biomass Magazine. 5 August 2020. Available online: https://www.canadianbiomassmagazine.ca/remotely-powerful-nine-rural-communities-experience-with-bioenergy-part-1/ (accessed on 5 February 2022).
20. Electricity Canada. Kwadacha Biomass Project—Canada's First-of-Its-Kind Biomass Facility. Electricity Canada. 2022. Available online: https://www.electricity.ca/programs/centre-of-excellence/kwadacha-biomass-project-canadas-first-of-its-kind-biomass-facility/ (accessed on 27 July 2023).
21. RCCbc. Rural Communities. RCCbc. Available online: https://rccbc.ca/rural-communities/ (accessed on 1 March 2023).
22. Loshin, P.; Steele, C. What is the ISO (International Organization for Standardization)? SearchDataCenter. Available online: https://www.techtarget.com/searchdatacenter/definition/ISO#:~:text=ISO%20(International%20Organization%20for%20Standardization)%20is%20a%20worldwide%20federation%20of,body%20representing%20each%20member%20country (accessed on 24 August 2022).
23. Lee, K.M.; Inaba, A. *Life Cycle Assessment: Best Practices of ISO 14040 Series*; Center for Ecodesign and LCA (CEL), Ajou University: Suwon-si, Republic of Korea, 2004.
24. Cowie, A.L.; Brandão, M.; Soimakallio, S. Quantifying the climate effects of forest-based bioenergy. *Manag. Glob. Warm.* **2019**, *2019*, 399–418. [CrossRef]
25. Curran, M.A. *Overview of Goal and Scope Definition in Life Cycle Assessment. LCA Compendium–The Complete World of Life Cycle Assessment*; Springer: Berlin/Heidelberg, Germany, 2016; pp. 1–62. [CrossRef]
26. Rochester Institute of Technology. What is Life Cycle Assessment (LCA)? RIT. July 2020. Available online: https://www.rit.edu/sustainabilityinstitute/blog/what-life-cycle-assessment-lca (accessed on 31 October 2022).
27. Mohan, M. Perovskite photovoltaics. In *Perovskite Photovoltaics*; Academic Press: Cambridge, MA, USA, 2018; pp. 447–480. [CrossRef]
28. Pa, A.; Craven, J.S.; Bi, X.T.; Melin, S.; Sokhansanj, S. Environmental footprints of British Columbia Wood pellets from a simplified life cycle analysis. *Int. J. Life Cycle Assess.* **2011**, *17*, 220–231. [CrossRef]
29. SimaPro. Ecoinvent: High-Quality LCI Database Integrated in SimaPro. SimaPro. 2021. Available online: https://simapro.com/databases/ecoinvent/#:~:text=The%20ecoinvent%20database%20is%20a,way%20than%20in%20previous%20versions (accessed on 27 August 2022).
30. Benedictine University Library. Research guides: Public health Research Guide: Primary & Secondary Data Definitions. Primary & Secondary Data Definitions—Public Health Research Guide—Research Guides at Benedictine University Library. April 2023. Available online: https://researchguides.ben.edu/c.php?g=282050&p=4036581 (accessed on 27 July 2023).
31. Athena. *A Cradle-to-Gate Life Cycle Assessment of Eastern Canadian Surfaced Dry Softwood Lumber*; Athena Sustainable Materials Institute: Ottawa, ON, Canada, 2018.

32. Government of Canada, P.S. and P.C. Fuel LCA Model Methodology: EN4-418/2020E-PDF. Government of Canada Publications—Canada.ca. 3 April 2013. Available online: https://publications.gc.ca/site/eng/9.893160/publication.html (accessed on 27 August 2022).
33. Pa, A.; Bi, X.T.; Sokhansanj, S. Evaluation of wood pellet application for residential heating in British Columbia based on a streamlined life cycle analysis. *Biomass Bioenergy* **2013**, *49*, 109–122. [CrossRef]
34. Sinclar Group. Premium Pellet. 2022. Available online: https://sinclar.com/premiumpellet/ (accessed on 26 March 2023).
35. Pa, A.A. Development of British Columbia Wood Pellet Life Cycle Inventory and Its Utilization in the Evaluation of Domestic Pellet Applications. Ph.D. Thesis, University of British Columbia, Vancouver, BC, Canada, 2010.
36. PRé Sustainability. SimaPro Database Manual Methods Library. 2022. Available online: https://www.google.com/url?sa=i&rct=j&q=&esrc=s&source=web&cd=&cad=rja&uact=8&ved=0CAIQw7AJahcKEwioxMm5lLWAAxUAAAAAHQAAAAAQAg&url=https%3A%2F%2Fsimapro.com%2Fwp-content%2Fuploads%2F2022%2F07%2FDatabaseManualMethods.pdf&psig=AOvVaw0WTJTimovUuBpKmUwRMEM0&ust=1690762788078489&opi=89978449 (accessed on 27 July 2023).
37. UPM. Energy Wood harvesting. UPM Forest Life. 16 June 2021. Available online: https://www.upmforestlife.com/interviews/harvesting-energy-wood (accessed on 25 August 2022).
38. Wellburn, G.V.; Kuhlberg, M. Forest Harvesting. The Canadian Encyclopedia. 25 October 2010. Available online: https://www.thecanadianencyclopedia.ca/en/Article/forest-harvesting (accessed on 25 August 2022).
39. Kryzanowski, T. Small-Scale Sawmilling on the Farm: Is it Right for Your Operation? Small Farm Canada. 1 September 2018. Available online: https://www.smallfarmcanada.ca/features/small-scale-sawmilling-on-the-farm-is-it-right-for-your-oper/ (accessed on 25 August 2022).
40. Lin, W.; Wang, J.; Grushecky, S.T.; Summerfield, D.; Gopalakrishnan, B. Energy consumption and efficiency of Appalachian Hardwood Sawmills. *For. Prod. J.* **2012**, *62*, 32–38. [CrossRef]
41. Uasuf, A.; Becker, G. Wood pellets production costs and energy consumption under different framework conditions in northeast Argentina. *Biomass Bioenergy* **2011**, *35*, 1357–1366. [CrossRef]
42. Xing, Y.F.; Xu, Y.H.; Shi, M.H.; Lian, Y.X. The impact of PM2. 5 on the human respiratory system. *J. Thorac. Dis.* **2016**, *8*, E69. [PubMed]
43. EPA. Technical Air Pollution Resources. EPA. November 2020. Available online: http://www.epa.gov/ttn/chief/faq/ap42faq.html#ratings (accessed on 30 August 2022).
44. Columbia, B. *2012 BC Best Practices Methodology for Quantifying Greenhouse Gas Emissions Including Guidance for Public Sector Organizations, Local Governments and Community Emissions*; Ministry of Environment: Victoria, BC, Canada, 2012.
45. Government of Canada. National Inventory Report 1990-2016: Greenhouse Gas Sources and Sinks in Canada. 2018. Available online: https://unfccc.int/document/65715 (accessed on 27 July 2023).
46. Yazdanpanah, F.; Sokhansanj, S.; Rezaei, H.; Jim Lim, C.; Lau, A.K.; Bi, X.T.; Melin, S.; Shankar, J.T.; Soo Kim, C.S. Measurement of Off-Gases in Wood Pellet Storage. IntechOpen. 26 February 2014. Available online: https://www.intechopen.com/chapters/46210 (accessed on 29 November 2022).
47. U.S. Environmental Protection Agency | US EPA. (n.d.). Available online: https://www.epa.gov/sites/default/files/2016-08/documents/biogenic-co2-accounting-framework-report-sept-2011.pdf (accessed on 30 November 2022).
48. Padilla-Rivera, A.; Barrette, J.; Blanchet, P.; Thiffault, E. Environmental performance of Eastern Canadian wood pellets as measured through life cycle assessment. *Forests* **2017**, *8*, 352. [CrossRef]
49. Vazifeh, Z.; Mafakheri, F.; An,, C. Biomass supply chain coordination for remote communities: A game-theoretic modeling and analysis approach. *Sustain. Cities Soc.* **2021**, *69*, 102819. [CrossRef]
50. Francesco, G.; Righi, S.; Dias, A.C.; Luís, T. Wood pellet as biofuel: A comparative life cycle analysis of a domestic and industrial production chain. In Proceedings of the 12th Italian LCA Network Conference, ENEA, Pescara, Italy, 11–12 June 2018; pp. 383–392.
51. Vazifeh, Z.; Bensebaa, F.; Shadbahr, J.; Gonzales-Calienes, G.; Mafakheri, F.; Benali, M.; Ebadian, M.; Vézina, P. Forestry based products as climate change solution: Integrating life cycle assessment with techno-economic analysis. *J. Environ. Manag.* **2023**, *330*, 117197. [CrossRef]