Development of Techno-economic Model for Assessment of Bio-hubs in Canada

Final Report

IEA Bioenergy: Task 43

May 2022

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Submitted by: Priyabrata Pradhan, Maryam Akbari, Roshni Mary Sebastian, Abhishek Dwivedi, Amit Kumar

Department of Mechanical Engineering, University of Alberta, Edmonton, Canada

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Contact information

For further information and clarification, please contact Dr. Amit Kumar. Contact details are given below.

Amit Kumar, Ph.D., P.Eng., FCSBE
Professor,
NSERC/Cenovus/Alberta Innovates Associate Industrial Research Chair in Energy and Environmental Systems Engineering,
Cenovus Energy Endowed Chair in Environmental Engineering,
Deputy Director - Future Energy Systems (FES),
Faculty of Engineering,
Department of Mechanical Engineering,
10-263 Donadeo Innovation Centre for Engineering,
9211 116 Street NW
University of Alberta,
Edmonton, Alberta, Canada T6G 1H9
Tel: +1-780-492-7797
E-mail to: Amit.Kumar@ualberta.ca
http://www.ualbertaenergysystems.ca

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AOU	Area of undertaking
bdt p.a.	Bone dry tonne per annum
C&D	Construction and demolition waste
CWD	Coarse wood debris
d	Day
dt	Dry tonne
EJ	Exajoule
FCI	Fixed capital investment
FMA	Forest management agreement
FMU	Forest management unit
FRMA	Forest Resources Management Act
GDP	Gross domestic product
GIS	Geographical Information System
GHG	Greenhouse gas
gt	Green tonne
HRD	Hardwood
IC	Indirect cost
IHS	Information Handling System
kL	kiloliter
LF	Location factor
odt	Oven dried tonne
ROI	Return on investment
SFMM	Strategic forest management model
SPF	Spruce-pine-fir
TDIC	Total direct and indirect cost
TEA	Techno-economic assessment
TIC	Total installed cost
TPEC	Total purchased equipment cost
y	Year

Executive Summary

There is a growing global concern about climate change, a concern largely attributed to our fossil-dependent economic system. In response to international commitments to reduce the impacts of global warming, the Canadian government is aiming for a transition to a low-carbon economy. Bioenergy from forest biomass is a potential solution to meeting Canada's climate change mitigation targets. The forest sector contributes significantly to Canada's gross domestic product (GDP) and employment. However, moving from print to electronic media has decreased the forest industry's revenue, especially in the pulp and paper sector. While forest resources in Canada are mostly used for pulp and lumber, they can also supply renewable energy and non-energy needs in a sustainable manner in the long-term. To reposition the forest industry in Canada and develop the bioeconomy, new practices need to be put in place to make main forest products, as well as by-products and residues, available in accessible locations and at a low cost. The study conducted a literature review to estimate the amount of biomass available in three Canadian regions and developed a framework to assess the economic viability of producing forest-based bioenergy products in bio-hubs. The bio-hub model aims to establish a value-added supply chain for increasing the accessibility and value of forest biomass while meeting the needs of biorefinery and biofuel industries. Bio-hubs serve as storage, loading, and processing facilities where biomass can be reloaded and transported to industries by different means. The bio-hubs may have different configurations, dedicated for operations like storage and reloading; storage, sorting, and reloading; storage, sorting, processing, and reloading; and/or storage, sorting, processing, conversion to intermediates, and reloading. There could be other configurations, too.

The overall objective of this research is to conduct techno-economic assessments (TEAs) of the bio-hubs in Canada. The specific objectives are to:

- review of the amount and type of biomass available in three Canadian regions to appropriately size and design the bio-hubs;
- calculate the cost of processing raw forest biomass at a bio-hub through several different pathways;
- estimate the overall cost of various forms of biomass feedstock that are ready to be supplied;
- develop the cost estimates for bio-hubs for three regions of Canada (western Canada, central Canada, and eastern Canada) considering the characteristics of the industry in these regions;
- develop a tool for the TEA of bio-hubs and make it "plug and play" for stakeholders in Canada and other jurisdictions;
- conduct a case study of a real bio-hub using the developed TEA tool.

This research is a first-of-its-kind study on the assessment of bio-hubs in Canada. This report summarizes the literature review on biomass feedstock availability. It discusses various pathways of bioproduct production. It also presents a detailed description of the development of techno-economic models and the tool for bio-hubs known as CANBIO-HUB.

The study uses a whole tree biomass yield of 84 odt/ha and a forest residue yield of 24.7 odt/ha to determine forest biomass distribution across Canada using a geographic information systems (GIS)-based approach. The highest harvested forest biomass yields per hectare are recorded in British Columbia and Alberta, respectively, at 361 and 278 m^3/ha. Yukon and the Northwest Territories record the lowest yields at 66 and 84 m^3/ha.

This report describes several bioproducts (firewood, bark, woodchips, regular pellets, torrefied pellets, biochar, and bio-oil) and highlights various production pathways to generate bioproducts from forestry operations. A conceptual diagram for the studied bio-hub can be seen in Figure E1.

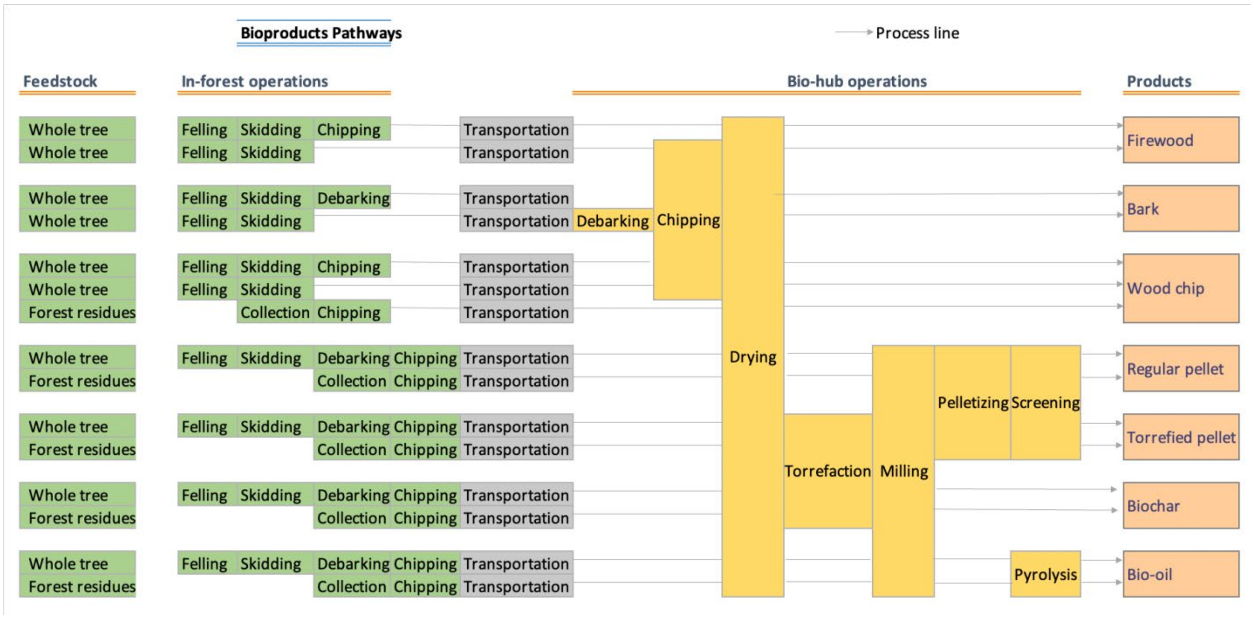


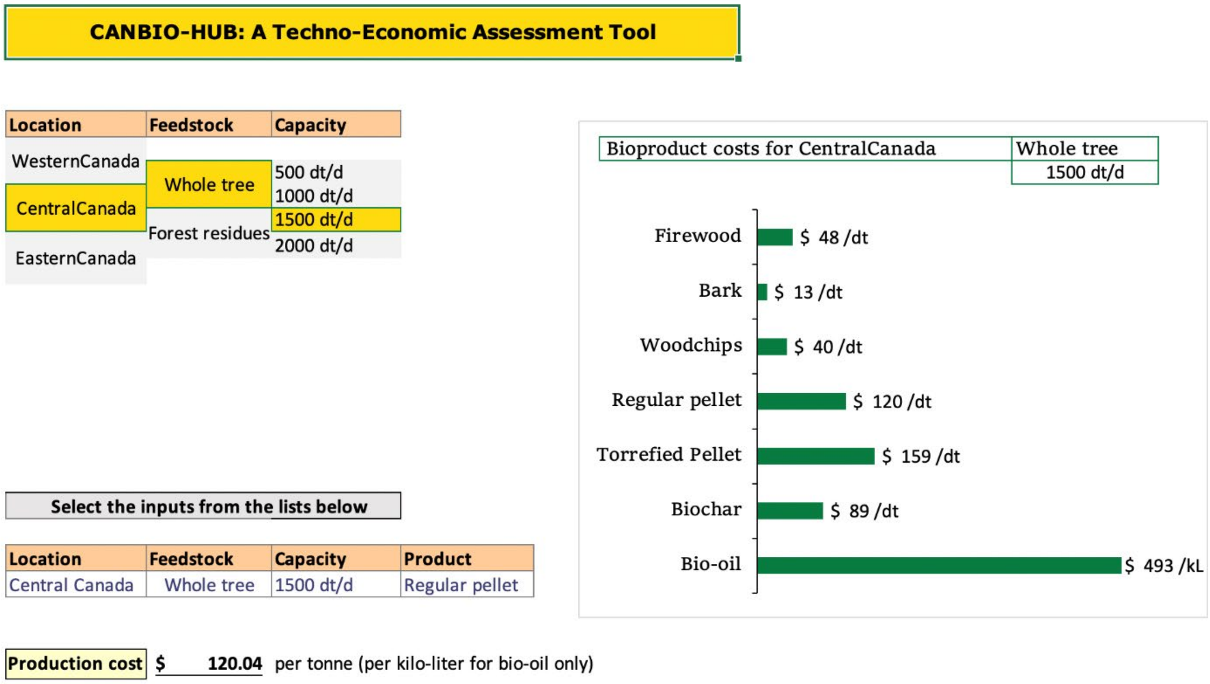
Figure E1: Bio-hub concept, bioproducts and production pathways for forest biomass processing.

A detailed description of the techno-economic assessment used to evaluate the production cost of the aforementioned bioproducts is included. This study gives an overview of general assumptions and cost estimation methods for bioproducts in the bio-hub facility. The key cost components of a bio-hub are capital cost, feedstock cost, and operating and maintenance costs.

The techno-economic models capture the effect of location, feedstock, and plant capacity on bioproduct costs. Under specific conditions (location - western Canada; feedstock - whole tree; capacity - 500,000 dt/y), the production costs of firewood, bark, wood chips, regular pellets, torrefied pellets, biochar, and bio-oil were estimated to be \$46/dt, \$13/dt, \$38/dt, \$118/dt, \$157/dt, \$87/dt, and \$0.49/L, respectively.

The models show a minor difference in the production cost of various bioproducts at different bio-hub location. For a bio-hub capacity 500,000 dt/y (1500 dt/d), the cost of firewood production from whole trees was estimated to be \$46.40/dt, \$47.90/dt, \$48.10/dt, for western Canada, central Canada, and eastern Canada, respectively. For the same capacity, the woodchip production cost was estimated to be \$38/dt for western Canada and \$40/dt for both central and western Canada. The production cost values of regular pellets and torrefied pellets were \$118/dt and \$157/dt, respectively, for a bio-hub capacity of 1500 dt/d located in western Canada. Similarly, the production cost values of pellets in central and eastern Canada were \$120/dt and \$158/dt for regular and torrefied pellets, respectively. Biochar production cost values were estimated to be \$87/dt for western Canada and \$89/dt for both central and eastern Canada at a bio-hub capacity of 1500 dt/d. Similarly, the bio-oil production cost value was estimated to be around \$490/kL for all three regions in Canada. All cost values for bioproducts discussed are for whole tree biomass feedstock.

In this study, we developed a spreadsheet-based TEA tool, CANBIO-HUB, which provides a user-friendly interface to calculate costs of various bioproducts in a bio-hub. The tool allows users to choose bio-hub location, type of feedstock, and plant capacity. Figure E2 shows an illustration of CANBIO-HUB.



CANBIO-HUB: A Techno-Economic Assessment Tool

Location	Feedstock	Capacity
WesternCanada	Whole tree	500 dt/d
CentralCanada	Forest residues	1000 dt/d
EasternCanada		1500 dt/d
		2000 dt/d

Select the inputs from the lists below

Location	Feedstock	Capacity	Product
Central Canada	Whole tree	1500 dt/d	Regular pellet

Production cost $ 120.04 per tonne (per kilo-liter for bio-oil only)

Figure E2: Illustration of bio-hub techno-economic assessment tool – CANBIO-HUB.

Two case studies were conducted. The first focuses on an economic assessment of willow plantations in Paintearth Mine in Alberta (a province in western Canada) for bioenergy production. The second case study is specific to Ontario (a province in eastern Canada) and focuses on the economic benefits of forest biomass use under several biomass use scenarios.

In northern Ontario, the cost of hardwood cost is from \$41.88 to \$54.60/m^3. For a whole tree density of 0.5 gt/m^3 at 50% moisture content, the hardwood cost is typically about \$41 to \$54/dt. In comparison, CANBIO-HUB shows a cost of \$48/dt for firewood production in central Canada.

This report describes the development of techno-economic models for the assessment of bio-hubs in Canada. CANBIO-HUB, was developed and validated with data obtained from case studies. Overall, the report provides a techno-economic perspective for the establishment of bio-hubs in Canada. The bio-hub will serve as a value-added supply chain model to enhance value of forest biomass for emerging biorefinery industries.

Section 1. Introduction

1.1 Background

Canada is covered by 347 million hectares of forest and the volume of forest wood is about 47 billion m^3 [1]. Annual energy use in Canada has been estimated to be 12.6 EJ/y, and fossil fuel-derived energy supply is 8.24 EJ/y [2, 3]. However, growing environmental concerns have led to a shift to interest in non-petroleum-based sources of energy. Using biomass-based resources decreases our dependency on fossil fuels. Unlike fossil fuels, using biomass for energy and fuels is considered nearly carbon neutral because the CO_2 released during the combustion of biomass-based fuels is absorbed by trees during their growth [4, 5].The forestry products and by-products are considered environmentally friendly [6].

The forest sector contributes significantly to Canada's gross domestic product (GDP) and employment. Forest resources in Canada have been mostly used for pulp and lumber. The move to electronic media from newsprint reduced forest industry revenue, especially in the pulp and paper sector [7]. Forest resources can supply renewable energy as well as non-energy needs in a sustainable manner in the long-term. For example, wood pellets can replace coal to provide heat and power. Forest biomass can be converted to liquid fuels through a range of processes. Forest residues, generated from logging operations, are normally burned to prevent forest fires. These can be used to produce fuels instead.

In order to reposition the forest industry in Canada, new practices need to be put in place to make forestry main products, as well as by-products and residues, available in accessible locations and at a low cost. Our model for a proposed bio-hub aims to establish a value-added supply chain to enhance the access and usefulness of forest resources, thus supporting emerging bio-based industries. These bio-hubs serve as terminal centres for storage, loading, and processing, where biomass can be further processed and transported to industries different means. The bio-hubs may be of different configurations, dedicated to operations like:

- Storage and reloading;
- Storage, sorting, and reloading;
- Storage, sorting, processing, and reloading;
- Storage, sorting, processing, conversion to intermediates, and reloading.

Other configurations can be developed based on the needs of and inputs from stakeholders. The processing of forest biomass is largely dependent on its end use. The commonly used processing techniques are drying, debarking, screening, comminution, and further upgrading through pelletization or torrefaction. Conversion to an intermediate liquid (e.g., bio-oil) is also an option.

Depending on the end product (i.e., firewood, bark, wood chips, regular pellets, torrefied pellets, bio-oil, biochar), forest biomass can undergo any of the following at a bio-hub: drying, debarking, chipping, crushing, pelletization, torrefaction, or pyrolysis.

To develop bio-hubs in Canada, thorough knowledge of the cost components is needed. This can be established through techno-economic models that incorporate forest biomass quantity, characteristics, type, and quality, and specifications for what is produced. This requires region-specific needs and forest biomass availability data. For example, forest biomass and its processing in western Canada are different than in eastern Canada. These inputs need to be developed for different regions of Canada. This study aims to address these gaps.

1.2 Objectives

The overall objective of this research is to conduct a techno-economic assessment (TEA) of proposed bio-hubs in Canada. The specific objectives are to:

- review the amount and type of biomass available in the three Canadian regions identified (western, central, eastern) to appropriately size and design the bio-hubs;
- calculate the cost of various pathways of processing raw forest biomass at a bio-hub;
- estimate the overall cost of various forms of biomass feedstock that are ready to be supplied;
- develop cost estimates for bio-hubs for the three regions in Canada based on the characteristics of the industry in the regions;
- develop a “plug and play” tool for TEAs of bio-hubs and make it available for stakeholders in Canada and elsewhere;
- conduct a case study of a real bio-hub using the developed TEA tool.

Section 2. Biomass resources

2.1 Forest biomass resources

Forest biomass is the largest biomass resource in Canada and is considered a suitable candidate to meet our bioenergy demands because of its high yield and wide geographic distribution[8]. Globally, wood and mill-based pellets are the most commonly used forest resources and have well-established supply chains [9]. Canada has more than 347 million hectares of forested land and another 300 million hectares of treed land, according to the National Forest Inventory[10]. This represents nearly 10% of the world's forest resources. 71% of the country's forests are owned by the provinces. About 58% of the inventoried forest is available for harvesting. Further, 0.4% of commercial forests is harvested each year [11]. Table 2-1 shows the forest area harvested and affected by insects or fire and the volume of forest biomass harvested [10]. In Canada, forestry is a 74 billion dollar/y industry [2], and, among the provinces, British Columbia has one of the most extensive forest resource management policies related to the biorefinery and bioenergy sector [12].

Table 2-1: Area under forestry activity [10]

Province	Insect-killed area (ha)	Fire-killed area (ha)	Harvested area (ha)	Volume harvested (m^3)
Alberta	993,908	49,119	91,875	25,525,462
British Columbia	5,471,065	1,215,851	183,788	66,379,661
Manitoba	1,639,571	176,677	7,644	1,070,198
New Brunswick	NA	568	81,439	9,341,187
Newfoundland and Labrador	38,417	700	8570	1,225,467
Northwest Territories	519,868	861,031	390	32,606
Nova Scotia	4,753	730	34,075	3,740,527
Ontario	1,319,653	112,337	131,688	15,123,867
Prince Edward Island	27	7	2,918	340,600
Quebec	4,733,185	38,392	202,130	30,026,645
Saskatchewan	567,727	399,563	21,872	3,919,485
Yukon	200,943	399,281	270	17,900

To effectively develop the forest bioeconomy in Canada, a detailed inventory of economically available biomass is essential. The three main forest residues in Canada are primary or harvest residues (including those unsuitable for lumber, material from stand thinning, and non-merchantable residuals from insect- or fire-affected trees), secondary residues or by-products of industrial operations (like bark, black liquor, etc.), and tertiary residues or by-products from construction and demolition waste (C & D) activities. Secondary residues are mostly used to meet energy demands in mills or to develop forest products. Tertiary residues are relatively underused due to limited supply. Bioenergy generation from forest residues predominantly depends on primary residues, with intermittent supply from other resources like logging following natural disturbances. Estimating the quantity of forest residue for bioenergy generation is complex. While theoretical estimates are stated by numerous researchers, the net available potential that could be recovered with economic feasibility, operational viability, and ecosystem balance is seldom explored.

2.2 Forest management activities in Canadian provinces

British Columbia

Canada's largest forest industry is in British Columbia (BC). BC harvested of about 68 million m^3annually from an area of 182,410 hectares in 2018 [13]. It also generates the most roadside harvest residues in the country (13.7 million bone try tonnes [bdt] per annum).There is significant potential in residues from the existing sustainable forest industries to substitute the fossil fuel energy demand by 21%(12 dry Mt/y) [14].

It is globally recognized that BC's forest management policy is one of the most rigorous and ecologically sustainable [12]. However, residues management has been a persistent issue. There is no forest biomass harvesting policy currently for bioenergy and biofuel production to regulate operations. For this reason, BC's biomass harvesting is focused on removing logging roadside and landings residues rather than entering blocks to remove material or harvesting low-commercial value stands. With a harvesting permit, forest companies have the rights to the woody biomass on their cut blocks for removing and harvesting any material considering the minimal requirements of the coarse wood debris (CWD) retention under the Forest and Range Practices Act [15]. Furthermore, these primary harvesting companies do not require any special licence or agreement for biomass harvesting.

Residual fibre from the roadside and cut block landings are other sources for which BC is looking for opportunities, and a high priority for the government and the forest sector in the province is the use of low-quality fibre from primary harvesting operations.

Alberta

According to 2018 information publicly available from the State of Canada's Forests: Annual Report 2020, Alberta has the fourth largest forest industry in Canada, by volume and area of forest harvested (27.1 million m^3; 93,438 hectares) [13].

The Government of Alberta promotes the growth and diversification of the forest sector. One way to diversify the sector is by using unused or underused forest biomass and transforming it into a source of clean energy, fuels, and chemicals. The arrangements for the use of this valuable biomass are the responsibility of the tenure holder and interested third parties [16]. Potential sources of biomass are roadside residues (this includes substandard quality trees or tree parts not considered useful during harvesting); trees destroyed by insects, disease, or fire, as well as trees and tops classified as undersized and not included in the annual allowable cut within merchantable stands that can be chipped; wood waste placed at mill sites and log sort yards; and pulp mill black liquor and separated lignin. In current harvesting practices, trees are harvested on site and skidded to the roadside. The roadside operation involves removing the branches, limbs, and tops. To prevent forest fires, the leftover harvest residues are burned.

Forest management agreements (FMAs) are long-term (generally 20-year) agreements signed by the Government of Alberta and forest harvest companies [17]. FMA holders have rights to perform harvesting operations in small areas known as forest management units (FMUs). There are 21 FMA holders with 42 FMUs in Alberta [18]. Each FMA holder operates a forestry mill such as a pulp mill, sawmill, panel board mill, or other type of integrated facility. There are 38 such mills in Alberta [19]. FMA holders can either use the harvested trees in their own operations or sell them to others.

Ontario

Ontario's managed forests, which are mostly boreal, are categorized as (1) crown forests (publicly owned) harvested for timber (29.40 million ha), (2) productive forests located north of the Area of Undertaking (AOU) (crown land south of 51 degrees north latitude) that are not harvested (8.28 million ha), (3) large parks (1.67 million ha), and (4) private forest land (5.34 million ha). All forests located in Ontario are managed; they are under the purview of Ontario's Wildland Fire Management Strategy developed in 2014 (OMNRF 2014). Because there is limited information available, we did not include non-productive forests in the far north here. The productive forests north of the AOU are like the forests at the AOU northern boundary.

The Forest Biofibre Policy addresses the harvesting of forest biomass in Ontario. According to this policy, "forest resources from Crown forests that are not normally being utilized for conventional forest products and that are made available under an approved management plan" are defined as forest biofibre [20]. Therefore, available forest biofibre consists of cull trees, treetops, trees that cannot be sold, and stands. It also includes salvaged trees after a natural ecosystem change. The policy does not apply to mill operations' by-products such as sawdust, wood shavings, wood chips, or bark. The policy provides the general guidelines for the allocation and use of forest biofibre in Ontario's Crown forests. The forest management planning regulates any use of forest biofibre. Therefore, all standards, regulations, and operating procedures applicable to conventional wood harvesting must be adhered to. Moreover, forest management is influenced by a vast array of national and provincial commitments, legislations, regulations, strategies, guidelines, procedures, standards, codes of practice, self-regulation, and agreements negotiated formally or informally. Forest management plans for each FMU are updated every 10 years by companies managing these forests in accordance with government regulations.

Quebec

About 20% of Canada's forest land is in Quebec, which has a dense forest 761,100 km^2 zone. Fifty-five percent of it is considered productive. Harvesting methods in Quebec are cut-to-length and 60% of residues are left at the roadside [14]. There is no province-wide policy in Quebec, but harvesting is regulated at the regional level. Nor is there a policy preventing the harvesting of whole trees, which makes up about half the province's logging [21].

Quebec's forest biomass can be an energy source. To help nourish the ecosystem, at least 30% of the woody material must be left in the forest. Moreover, harvesting biomass from logging and piling areas has a positive effect by reducing losses in productive areas.

Saskatchewan

Saskatchewan has the country's second smallest logged area and volume harvested (20,303 ha; 3.7 million m^3) (in 2018) [13] (Prince Edward Island has the smallest). Forest biomass use for power in Saskatchewan is the main reason for the industry's need to readjust its economics by developing new products following the decline in revenue from the traditional forest industry. The main source of biomass for energy production in Saskatchewan is mill residues, augmented by waste from heritage piles at mills. Other biomass sources are roadside residues from logging operations and residual standing wood of below-merchantable size and silvicultural debris. Materials from urban construction or horticultural cuttings can be considered another source. Fast-growing purpose-grown biomass that can offer a substantial economic opportunity is another.

Manitoba

Although the harvest area in Manitoba is twice as large (9,439 ha in 2018) as in Saskatchewan, both harvest a similar volume of wood (1.3 million m^3) [15]. After Newfoundland and Labrador and Prince Edward Island, Manitoba is estimated to have the fewest roadside residues of 0.329 million bdt per annum [15]. Merchantable timber and the amount of material left in a forest reregulated under the Forest Act. Unmerchantable wood can be harvested and used with authorization. Biomass opportunities are assessed on a site-by-site basis, and instructions as well as permits issued are disclosed in the Timber Sale Agreements.

Nova Scotia

In 2018, Nova Scotia harvested about one-twelfth the volume of wood harvested in BC (about 3.4 million $m^3$was harvested on 31,151 hectares). In Nova Scotia, biomass is mostly roundwood; limbs and treetops are left in the forest, as well as unmerchantable trees (such as poplar species) and trees unsuitable for pulp (dead and rotten trees). The government is drafting regulations to define whether and how much treetops and limbs can be used.

Forest biomass harvesting specifications in Nova Scotia [22]:

- There may be a penalty for using more than 3.0 m^3/ha or 3% of the harvested volume of total merchantable waste.
- There should not be more than 5% of the harvested area bared to mineral soil or covered with windrow material.
- The maximum merchantable stems and basal area that can be removed while maintaining a basal area $\geq$ 18 m^2/ha should not exceed 30% in any 10-year period.

Prince Edward Island

On Prince Edward Island, the forest ecoregions are Acadian Forest, temperate broadleaf and mixed forest [23]. It has been found that the total forested area (including harvested forest sites that could not be determined if they will to return to forest or converted to another use) accounted for 45% of the provincial area(255,780 ha) [23]. Biomass including wood, sawmill residues, and municipal waste provides 10% of the energy in Prince Edward Island.

Prince Edward Island has the following requirements for biomass projects with public investment [22]:

- Standards in the Ecosystem-based Forest Management Standards Manual must be followed for planning pre-harvest management.
- Standards for harvesting in the Ecosystem-based Forest Management Standards Manual must be followed.
- Whole tree harvest is allowed for commercial thinning and other non-clear-cut harvests, but stumps must be left in the forest;
- Every biomass harvest area must be mapped through GPS and the maps filed with the Forests, Fish, and Wildlife Division.

Newfoundland and Labrador

Canada's smallest area (7,925 ha) and volume (about 1.3 million m^3 as of 2018) of forest cut is in Newfoundland and Labrador. Excluding Prince Edward Island, which has none, Newfoundland and Labrador is estimated to have less roadside debris than all other provinces (0.8% of the Canadian total) [14].

There is a substantial emphasis on developing forest management guidelines that will lead to forest sustainability, thereby minimizing environmental impacts and encouraging the development of the forest industry. Provincial guidelines and policies require that branches and foliage be left in the forest to maintain nutrients and provide mats to reduce ground disturbance by forestry equipment. In special circumstances, such as when forest stands have been affected by insects or diseases, or when clearing rights-of-way, this requirement is not necessary. Whole trees are not harvested in Newfoundland currently [24]. The current forest biomass harvesting guideline includes not harvesting full trees, leaving limbs and treetops in the forest, and retaining a specific number of trees per hectare for wildlife and future woody debris collection [22].

Northwest Territories

Around 70 million ha of the Northwest Territories (NWT) is south of the tree line [25] and, of that, the forests encompass 33.3 million ha and comprise 28% of the Canadian boreal forest. Currently, around 30,000 m^3 are harvested per year in the NWT, two-thirds of which is used as fuel [22]. In the NWT, wood fuel is used in about 60% of homes. A northern pellet-making business is being planned in collaboration with First Nations in the NWT.

New Brunswick

In 2018, 74,469 ha (9.3 million m^3) of forest were harvested in New Brunswick [13]. The estimated roadside residues in the province are 0.848 million bdt p.a., one-sixteenth that of BC's [14]. New Brunswick was the first province to have a defined forest biomass harvesting policy, released in 2008 as New Brunswick's Crown Land Forest Biomass Harvesting Policy [26]. The eligibility for biomass harvesting in a forest stand is determined by the GIS-based Forest Biomass Decision Support System. This system uses the latest information available on climate, soils, forest growth, and yield.

2.3 Quantification of forest biomass resources

Estimation of whole tree biomass yield

Given the challenge to identify the amount of forest biomass generated in each province due to the different harvesting and recovery policies across Canada, we used published papers and government databases. The volume of forest biomass harvested was taken from the Natural Forest Industry and Natural Resources Canada [10, 27]. To determine the availability of the sustainable biomass, each study area was assessed to estimate the amount of harvestable biomass. Whole tree biomass yield was estimated using data obtained from the State of Canada's Forests: Annual Report, 2020. Whole tree biomass yield was calculated using the following formula:

$$\mathbf{Q_{WT} = {}^{V}\!/_{A} \times d \times mc \times 10^{-4}} \qquad \textbf{Equation 2-1}$$

where Q_{WT} is whole tree biomass yield (odt/ha), V is volume harvested (m^3), A is area harvested (m^2), d is density of a whole tree (gt/m^3), and mc is moisture correction factor.

The values of d and mc are assumed to be 0.5 $gt/m^3$and 50% (wet-basis), respectively.

Estimation of forest residue

Theoretical estimation and geographical distribution of biomass resources are essential to assess operational feasibility and economic viability. The potential of whole tree biomass is dependent on the different harvesting and recovery policies. The major categories of biomass considered here are coniferous, deciduous, and mixed forest [28]. ArcMap 10.4 was used in this analysis to understand the geographical distribution of the biomass density. In the first stage, the study areas, namely western, eastern, and central Canada, were extracted from census division shape files. These were used as the input for Geographical Information System (GIS)analysis along with Canada's land cover [28]. The desired biomass categories were subsequently extracted for the various bio-hub locations through GIS analysis. The categories were integrated with the biomass yield per hectare to estimate the total biomass available in each study area as well as by province. Wood et al. [2] reported the average biomass yield for Alberta to be 78 oven dry tonnes per hectare (odt/ha), while Kumar et al. [29] reported the whole forest biomass yield to be 84 odt/ha. A 20% residue yield from these residues, equal to a blended yield of 24.7 dry tonnes of residue per harvested hectare, is assumed here [29]. Biomass availability was estimated using the following equation:

$$\mathbf{Q = \sum_{i=1}^{n} ka_i} \qquad \textbf{Equation 2-2}$$

where Q is the total biomass available, k is the biomass yield (odt/ha), a_i is the area of polygons (ha) constituting the study area, and n is the number of polygons into which the study area is divided in the GIS environment. Forest residue yield is assumed to be 20% of the total biomass yield.

Quantification and geographical distribution

About 58% of the inventoried forest in Canada is available for harvesting, and 0.4% of commercial forests is harvested each year [11]. In 2018, the highest yields per hectare were recorded in British Columbia and Alberta, respectively, at 375 and 291 m^3/ha [15]. Yukon and the Northwest Territories recorded the lowest yields at 66 and 84 m^3/ha, respectively. This is shown in Figure 2-1, which also shows that total forest biomass is highest in British Columbia. Further, British Columbia has extensive forest management policies in place.

The Northwest Territories and Yukon have the lowest residue potential, as most of the residue generated is used locally and thus not available for other uses. Provinces like Alberta and Saskatchewan have a significant residue yield potential of nearly 24 and 15 odt/ha. Because forest residue is a significant biomass source with applications in bioenergy and biorefinery configurations, these estimates can help frame valorization strategies. Table 2-2 shows the estimated forest biomass yield in different Canadian provinces and territories.

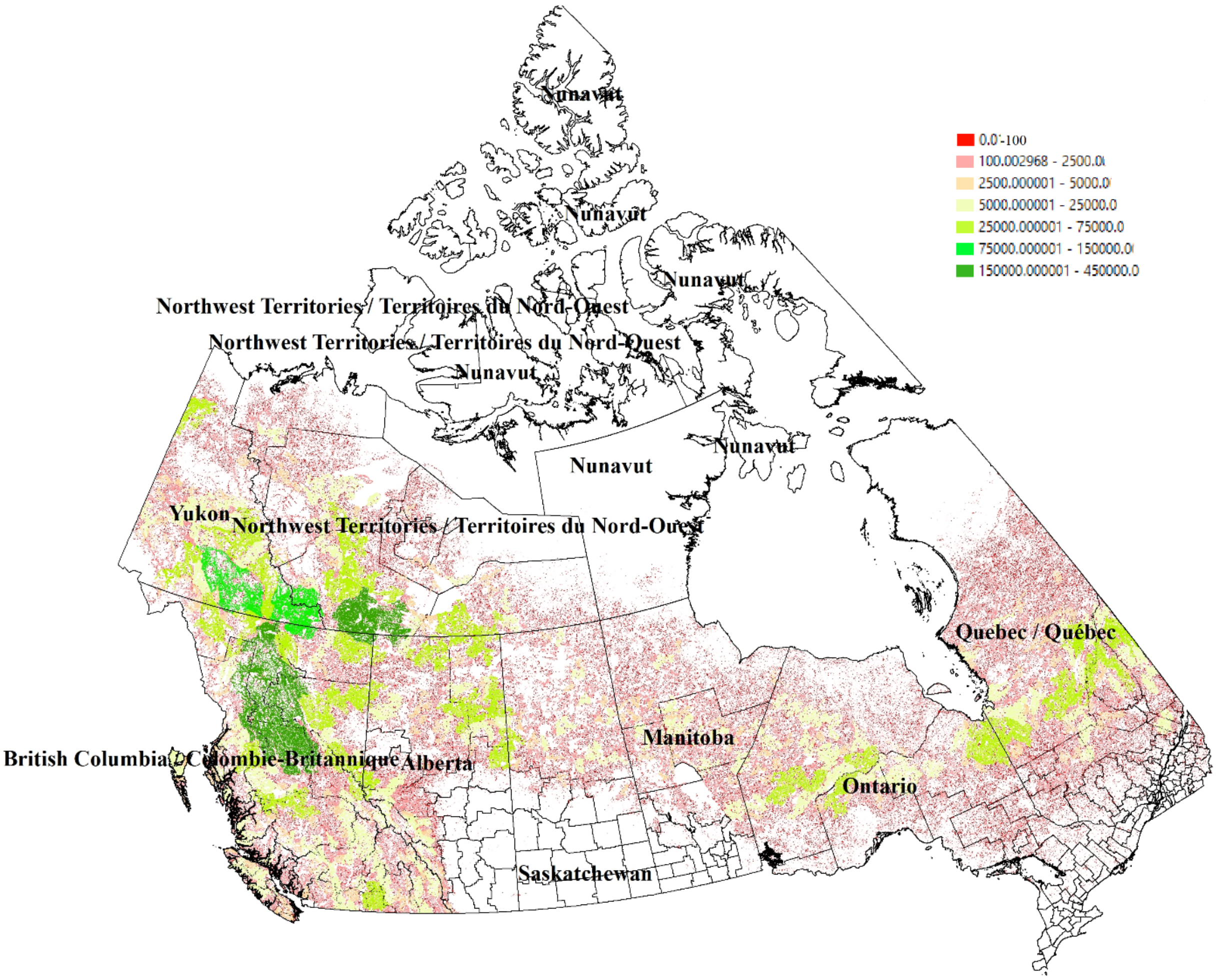


Figure 2-1: Forest residue biomass in Canada as developed based on the GIS modelling

Table 2-2: Forest biomass yield in Canada by province

Province	Estimated whole tree biomass yield (odt/ha)	Estimated forest residue biomass yield (odt/ha)
Alberta	72.6	24.1
British Columbia	93.8	31.2
Manitoba	35.0	12.1
New Brunswick	31.4	9.9
Newfoundland and Labrador	42.9	12.4
Northwest Territories	25.4	7.2
Nova Scotia	27.0	9.5
Ontario	27.7	9.9
Prince Edward Island	30.8	10.1
Quebec	35.9	12.8
Saskatchewan	45.5	15.5
Yukon	14.5	5.7

2.4 Summary

With efforts to minimize GHG emissions while meeting rising energy demands, renewable energy sources have become a “green” energy hotspot. Canada, with its abundant natural resources, has significant potential to reduce its reliance on fossil fuels and incorporate bio-based energy sources into the supply chain. This is evident from the country’s recent conscious policies and actions to transition to a bio-based economy. In order to facilitate this transition, it is essential to assess the amount of biomass available in that can be sustainably used. Accordingly, Canada has a potential of generating approximately 21 million odt of forest residue. While the territories were found to have the lowest forest residue yield (≈5-8 odt/ha), the provinces of British Columbia and Alberta had relatively higher yields of 31.2 and 24.1 odt/ha, respectively. Similarly, the whole tree biomass yield is highest (93.8 odt/ha) for the province of British Columbia followed by Alberta (72.6 odt/ha). The potential losses were accounted for during the quantification, thus giving an estimate of the net available residue. The estimated yields shall be used in the subsequent stages of the study to determine the costs for processing.

Section 3. Bioproducts and production pathways

This section describes several bioproducts – firewood, bark, woodchips, regular pellets, torrefied pellets, biochar, and bio-oil– produced at bio-hubs. The production pathways for all bioproducts are also discussed.

3.1 Firewood

Firewood is a clean, safe, convenient (easily accessible in most areas), and efficient renewable source of energy [30]. The split log cut is used mainly in households to produce heat and is largely provided from local forests and sold locally [31]. Firewood also can be a by-product of logging operations [32]. However, firewood supply from logging limited compared to its total supply [32]. Although different tree species have different properties and firewood can be produced from all of them, some are not ideal for use in open fireplaces because they spark [33]. Softwoods have less heating value per unit volume than hardwoods because they are less dense; hardwoods' higher heating value per unit volume leads to longer burning [30]. Although hardwoods are preferred, especially in the east and central Canada, softwoods are suitable fuel for spring and fall [34], and those in the coldest parts of Canada have access to softwood only [34].

Firewood is typically sold by volume as a full cord. A stacked cord is 4x4x8 ft^3. The volume of wood is roughly 70% because of the gaps between the logs [31]. The energy content of firewood is affected mostly by its moisture content, and moisture content is the most influential factor in determining firewood quality [33]. A moisture content of 25% is the ideal amount for efficient burning. The term for the natural drying of firewood (by wind or sunlight) is seasoning. Increasing the surface and contact areas of firewood by splitting it decreases the drying time. Seasoned wood storage is also important; the wood should be protected from snow and rain [31]. The key specifications of firewood according to CAN/CSA-ISO 17225 Part 5 Standard are described in detail in earlier published literature [31].

With increasing focus on the use of sustainable and green sources of energy and also surging energy consumption worldwide, the use of wood resources such as firewood for space heating is gaining interest [30]. Firewood is anticipated to be an important component in the future bioenergy industry [32]. It makes up more than 50% of the woody biomass used in the domestic sector for energy production in many European countries [33]. Pellets or logs are used mainly in a boiler or boiler-burner system [33]. According to Natural Resources Canada, in 2017 firewood was the 3rd largest energy source, providing 11% of heating energy in the residential sector [35].

Although firewood is an energy source in Canada, its production is not clearly known. This is because there is no specific agency responsible for firewood production or the related data in some parts of Canada [35]. The following section describes the development of process cost models for estimating the production cost of firewood through various pathways. The main objective of this section is to develop techno-economic models to estimate the production cost of firewood through various pathways.

Firewood production pathways

The two pathways to produce firewood are shown in Figure 3-1. The pathways are:

1. Pathway 1 starts with the felling of the whole tree, followed by skidding and chipping, which take place in the forest. The chipped tree is then transported to the bio-hub to be dried.
2. Pathway 2 is similar to the Pathway 1 with the difference that chipping the whole tree happens in the bio-hub rather than in the forest. In this case, the tree logs are transported to the bio-hub.

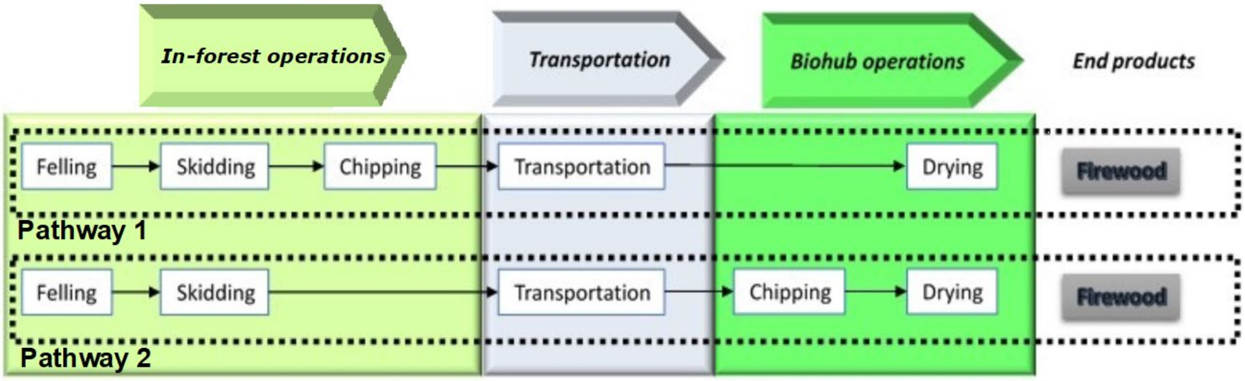


Figure 3-1: Firewood production pathway

It could be challenging to transport of whole tree. The whole tree is therefore delimbed on the roadside before transportation via truck.

3.2 Bark

Forest biomass includes different parts of trees, not only the stem but also the bark, branches, leaves, etc. [36]. Bark, which has a remarkably high lignin content compared to white wood (tree yielding a light-colored wood),was considered a burden (difficult to handle) and was usually incinerated (along with other wood residues) until several years ago [37, 38]. There is a growing interest in non-traditional biomass residues including bark [37]. Bark is now used for energy production such as for heat and steam production in pulp and paper mills as well as lumber mills [36, 39]. Low-grade fuels can be produced from chipped bark [39]. Bark makes up a significant portion of hog fuel, which is mainly used for on-site production of heat and power in processing mills [38]. Even though there is a market for bark, its production volumes are not accurately surveyed [37]. British Columbia and Alberta have several zones with estimated residue surplus, while the zones in Ontario, Saskatchewan, Quebec, Nova Scotia, and New Brunswick are mostly located around bark piles [37]. With a production of more than 10 million dry tonnes in Canada, bark can be considered an important source of biomass energy [37]. Although mill residues such as bark usually have fairly low production costs in Canada, handling and transportation costs may lead to a high final cost and hence make bark uneconomical to users far from its source [37].

Bark removal from wood requires extra care to minimize the amount of wood removed from logs [39]. It is suggested that logs be debarked in the forest before they are dried since the bond between bark and wood fibres increases with decreasing moisture content [40]. Logs can be debarked in summer in the forest when they are not frozen. There are concerns about debarking in winter as the bark limit in the wood chips produced may exceed the allowable limit during this time if the tree is frozen [39, 41]. Hence, some treatments before debarking may be required to improve debarking efficiency, especially in the winter when logs are frozen [41], depending on which debarking process is used in the bio-hub.

There are several debarker types: ring, cambio, hydraulic-oscillating, rosser-head, drum, etc. [39]. For short rotation trees in western North America, chain flail delimbing and debarking is the most popular means of residue separation from wood chips [42]. For satellite chipping, drum debarkers are preferred for the processing of small trees. Flail equipment can also effectively debark small trees and can lead to the < 1% bark level in wood chips specified by many industries [42]. That said, the loss of white fibre from wood is a concern associated with flail debarkers.

Bark production pathways

The pathways for the production of bark are shown in Figure 3-2.

1. Pathway 1 starts with the felling of the whole tree, followed by whole tree skidding and delimbing of the limbs and tops, both of which happen in the forest. The tree is then transported to a bio-hub to be debarked. Logs are produced as the co-products of this process and are transported to different mills or elsewhere depending on their further use.
2. In Pathway 2, bark produced in sawmills is transported to a bio-hub, where it is stored with bark from other sources.
3. In Pathway 3, bark is the by-product of in-forest logging operations. Logs are produced after trees are felled, skidded to the roadside, delimbed and debarked, and the debarked logs are transported to sawmills or other facilities for further operations. The bark left behind in the forest is transported to a bio-hub, where it is stored along with bark from other sources.

In the first stage in each pathway, whole trees are cut by a feller/buncher and skidded to the landing area by a loader where they are debarked [42]. For trees weighing over 50 kg, more than 95% of the bark is in the bark stream after debarking [42].

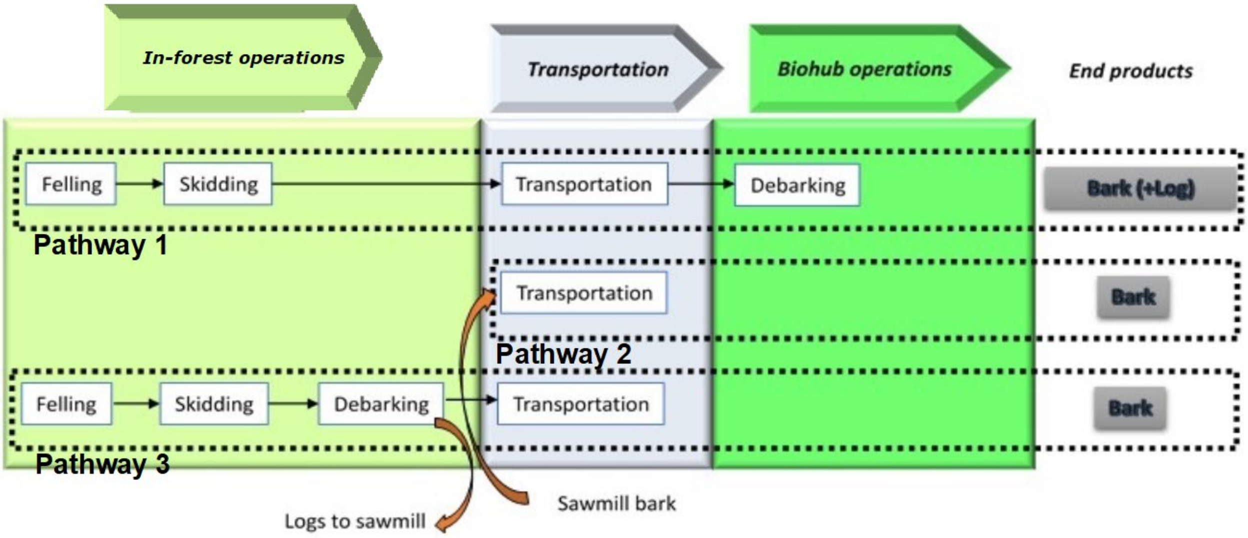


Figure 3-2: Bark production pathways

3.3 Wood chips

Wood chips are generally produced as the co-products of processes in sawmills. In BC, lumber production generates a significant amount of wood chips, around 40% of the volume of the harvested lumber [38]. Wood waste generated through wood processing operations and low-quality logs are also converted to wood chips [39].

In pulp mills in eastern Canada, full logs are converted to wood chips [38]. In some other locations in eastern Canada as well as in central Canada, BC, and AB, whole trees are debarked as well as delimbed and chipped in a single continuous operation at or very close to the harvest point [38]. For example, DMI's pulp mill in Alberta produces wood chips (instead of pulpwood) using nine in-the-woods chippers [38]. In their original condition (wet), wood chips can be used as the feedstock for biochemical conversion processes and in some thermochemical routes. If dried, they can be the feedstock of many thermochemical routes [38].

The quality of the end product (biofuel) produced from wood chips and energy production efficiency are affected by the quality of the wood chips. Hence, checking the quality of the wood chips and certifying them according to the defined standards and their end use are suggested [43]. Target wood chip dimensions are 15-20 mm long and wide and 4-6 mm thick. This size enables most chemical and mechanical pulping systems to operate efficiently and produce uniform fibres [44]. End-product quality and chipping efficiency are also affected by operator experience (motor skills, work techniques, and decision-making abilities), as reported in several studies and explained in detail by Moskalik et al. [43].

Many studies have investigated the effects of biomass characteristics on chipping efficiency, improving wood chip production efficiency, storage-related issues, enhancing the quality of wood chips by decreasing water content, and technological progress in helping forest energy procurement [43]. Transportation distance to major consumers, division of forest areas, as well as the heating value and bulk density of wood chips, are the parameters that most influence the economic feasibility of wood chip production [43].

Wood chips production pathways

The four wood chip production pathways are shown in Figure 3-3.

1. In Pathway 1, whole trees are felled, skidded to the roadside, and chipped, all of it in the forest. The wood chips are then transported to a bio-hub. There, the chips are dried and the end product (wood chips) is produced.
2. Pathway 2 is similar to Pathway 1 except that chipping takes place in the bio-hub.
3. In Pathway 3, the by-products of debarking and chipping produced during operations in the bio-hub are, as in Pathways1 and 2, dried to produce wood chips.
4. In Pathway 4, sawmill residues are transported to a bio-hub where they are treated in a similar way as the by-products in Pathways 1, 2 and 3.
5. In Pathway 5, harvesting residues, the by-products of logging operations in the forest, are collected, chipped, and then transported to a bio-hub for the production of wood chips (as in the other pathways).

The feedstock for the 3rd, 4thand 5th pathways is the wood from the debarking/chipping operations, the lumber industry, and the harvesting of trees, respectively. The residues are left by the side of the road after tree harvesting but they can be collected and used as a source of clean energy. Normally, of the dry mass of a tree,3-8% is needles or leaves, 3-8% is bark, 7-15% is branches, and 65-80% is the trunk. Softwoods include conifers such as spruce, pine, and fir. Dry pine contains 40% cellulose, 28% hemicelluloses, 28% lignin, and 4% extractives. Lignin can make up to 48% of the bark [45]. A growing tree's moisture content is around 50% (35% in summer, 65% in winter). Among all wood constituents, extractives have the highest heating value [46].

This research focuses on recovering harvest residues, as shown in the 5th pathway in Figure 3-3. The approach in the 5th pathway is the recovery and then reuse of tops and limbs left on the side of logging roads. These roadside residues make up15-25% of the total forest biomass. In lumber production there is growing emphasis on "cut-to-fit" in the forest to the economic length as it eliminates the costs of transporting wastes or residues to the mill [46]. This practice increases harvest residue production to the upper range of 25%. Here, 20% (a good yield from a forest site) residue was used, since logging and pulping operations currently use such sites for harvest[46]. Because of the northern climate and poor soil conditions, Alberta's forests are harvested based on an average rotation of 80-120 years. Here, a rotation of 100 years is considered, leading to a yield of 0.247 dry tonnes of residue per net harvested hectare [46].

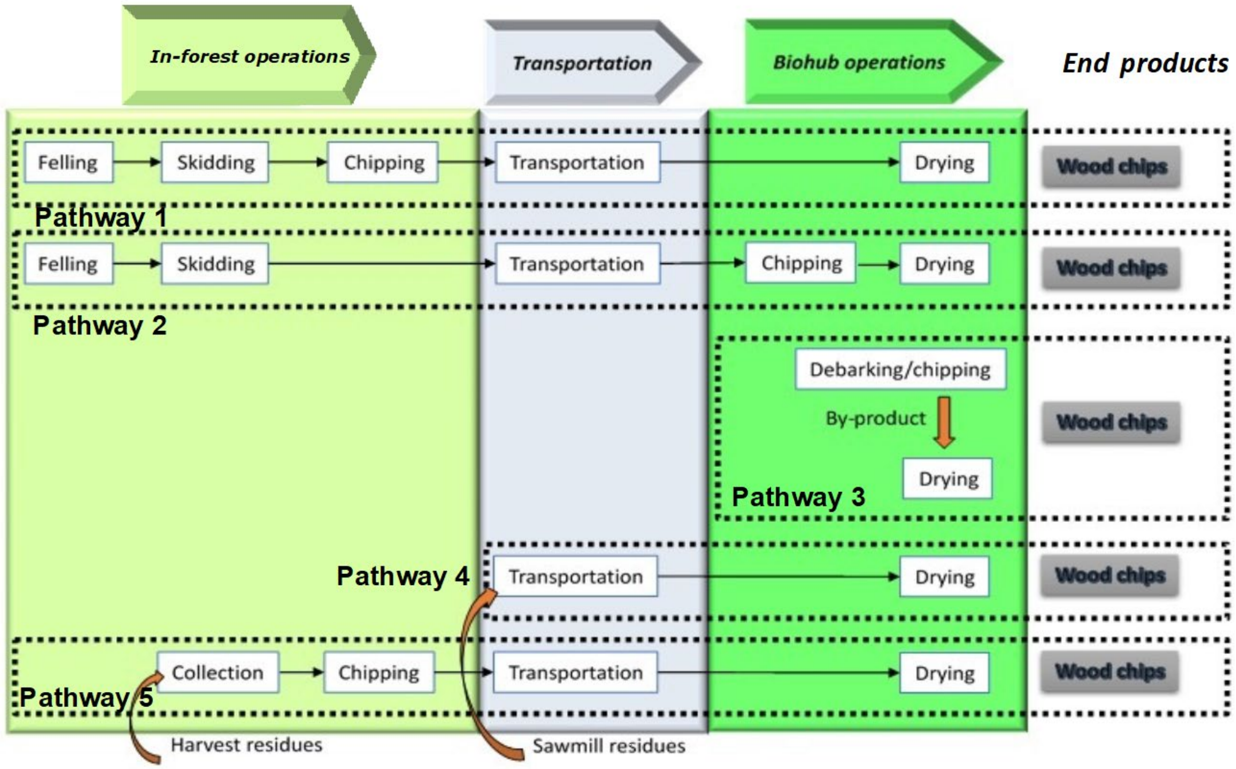


Figure 3-3: Wood chip production pathways

3.4 Regular pellets

Raw biomass such as wood has a low energy density (2-3 GJ/m^3), heating value (9-12 MJ/kg), and bulk density (200-250 kg/m^3), yet it has a high volatile content (70-75 %) and moisture content (30-45 %). It also suffers from poor grindability and is hydrophilic and heterogeneous. Solid fossil fuels (like coal), however, offer a higher energy density (18.4-23.8 GJ/m^3), heating value (23-28 MJ/kg), and bulk density (800-850 kg/m^3) as well as lower volatile content (15-30 %) and moisture content (10-15 %). These also have good grindability and are hydrophilic and homogenous [70, 71, 74, 79, 81]. For the raw biomass to be used as a replacement for fossil fuels, it is necessary to improve its properties.

Pelletization is one of the biomass pre-processing techniques. Biomass is collected, then it is sent to a chipper where chips are produced. The chipped biomass is transported to a mill. The feedstock for most current pellet production is sawdust, a residue from sawmills. Biomass should be dried before pelletization. Pelletization increases the bulk density and heating value of the biomass, both of which are necessary to make co-firing with coal more economically feasible [47, 48].

Regular pellets production pathways

The pathways for regular pellet production are shown in Figure 3-4.

1. In Pathway 1, whole trees are felled, skidded, debarked, and chipped in the forest. The wood chips are transported to a bio-hub, where they are dried, ground, screened and then pelletized.
2. Similar to Pathway 1, in Pathway 2 the by-products of debarking and chipping produced inside the bio-hub are dried, ground, screened, and pelletized to produce wood pellets.
3. In Pathway 3, sawmill residues are transported to the bio-hub, where they are treated like the chips in Pathways 1 and 2.
4. In Pathway 4, harvesting residues, the by-products of logging operations in the forest, are collected, chipped, and then transported to a bio-hub to produce pellets (as in the other pathways). Logs are transported to sawmills or other facilities for further treatment.

The feedstock for the 2nd, 3rd, and 4th pathways is the wood residues from the debarking/chipping operations, the lumber industry, and the harvesting of trees, respectively. The residues are left by the side of the road after tree harvesting but they can be collected to be used as a source of energy. Since existing roads for transporting logs are used for residue transportation, no construction costs are assumed here [46]. To reduce feedstock size, biomass is processed in a grinder and then ground to a particle size of 3.2 mm or less in a hammer mill [49]. By changing the mesh screen size, the desired particle size can be achieved in the hammer mill. Wet biomass is dried in a conventional dryer to the moisture content desired. In this study, it is assumed that there are no losses of extractives or volatiles during drying and that the only exhaust from the system is moisture [50].

The ground biomass enters a pellet mill where it is extruded with a roller and pushed through a die hole, where it is compressed into pellets. Several parameters like die pressure and temperature as well as die and roller configuration can affect the pellet mill's efficiency [51]. Once formed, the pellets are air-cooled to 25°C. The feed material’s flow rate to the mill is controlled by a vibratory feeder. In this study, neither the flowability issues of the feedstocks, the addition of additives, nor the recycling of fines were included based on the information in a paper by Adapa et al. [52].

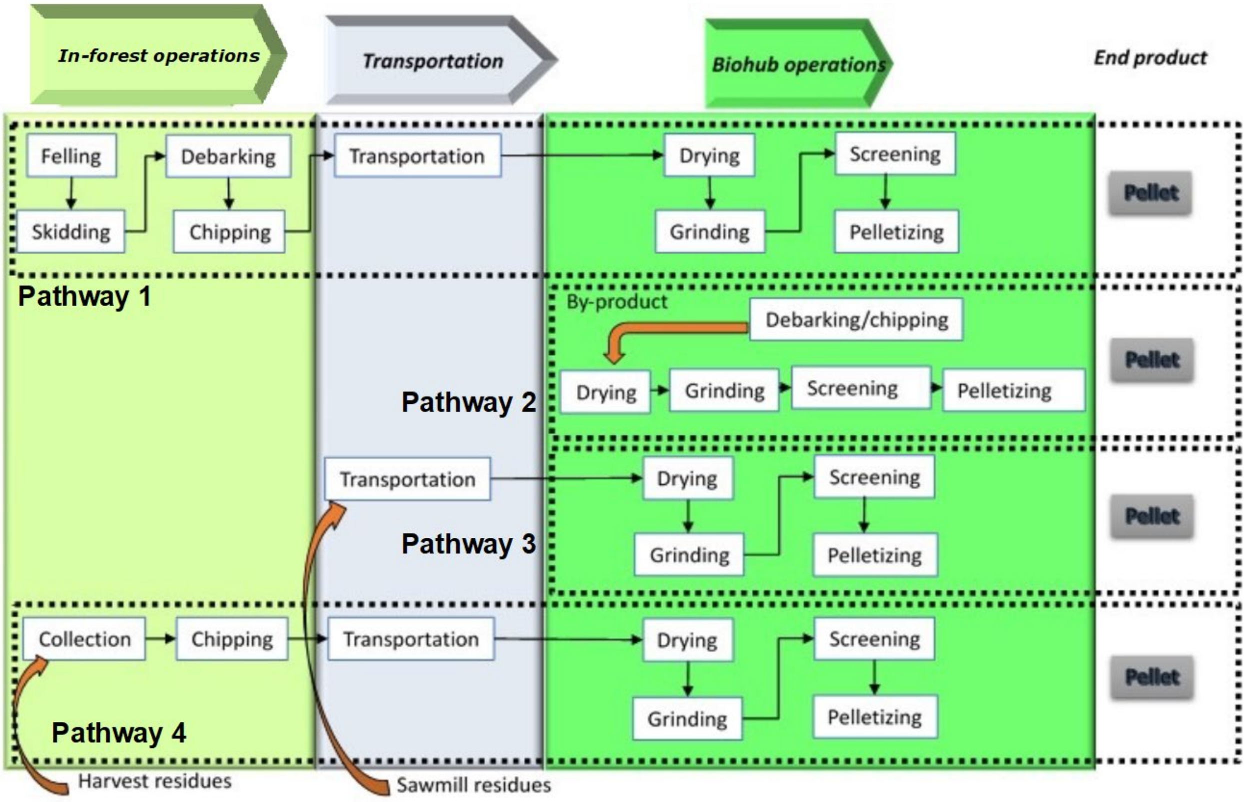


Figure 3-4: Regular pellet production pathways

3.5 Torrefied pellets

The properties that make biomass disadvantageous as a fuel compared to coal are low bulk density, low heating value, low friability, high water content, and non-homogeneity [53]. The characteristics of biomass pellets are an improvement over raw biomass and hence are superior in terms of co-firing with coal [53]. However, regular pellets still suffer from some drawbacks as a fuel. They absorb moisture and crumble and therefore require special considerations during transportation, handling, and storage [53]. Thus, thermal pre-treatment of raw biomass (such as torrefaction) prior to pelletization has attracted considerable attention recently [53]. Torrefaction can allow for increased co-firing rates. Energy requirements for biomass size reduction reduces considerably after torrefaction [53]. Torrefaction enhances the heating value of biomass by up to 21% and improves the friability of raw biomass [53].

Torrefaction prior to pelletization improves the grindability of the pellets [54] and improves the heating value and hydrophobicity [55]. Pelletization improves the energy density of torrefied wood compared to conventional wood pellets [56, 57]. A significant advantage of improved energy density is a decrease in pellet transportation cost and emissions per unit energy content.

The ground torrefied biomass is fed into a pellet mill and passed through a die hole to form pellets. After pelletization, pellets are air-cooled from 95-100 °C to 25 °C. Note that, the efficiency of a pellet mill depends on parameters such as die temperature, pressure, and die and roller configuration [51].

The integration of torrefaction and pelletization has been widely investigated by Bergman et al. [58, 59]. This process is of high interest because of its advantages over conventional pellet production [60-66]. The most important advantage is its economical superiority. Although torrefaction before pelletization has several advantages, it may lower the durability of the torrefied pellet compared to the conventional pellet [67]. Severe torrefaction conditions lead to challenges in producing durable pellets [67]. However, as Bergman found, torrefied pellets are more durable than conventional/regular pellets [59]. That said, binders may be needed for torrefied biomass pelletization since torrefaction at temperatures higher than 300°C lowers the lignin content, which is the natural pelletization binder [68, 69]. With proper consideration of the compression ratio, moisture, and particle size, torrefied biomass can be pelletized without the addition of a binder (as evidenced in some industrial cases) [68, 70]. Although the torrefaction process has been studied for more than a decade, the economics of combined torrefaction and pelletization needs more investigation [67].

Torrefied pellets production pathways

The pathways to produce torrefied pellets are shown in Figure 3-5.

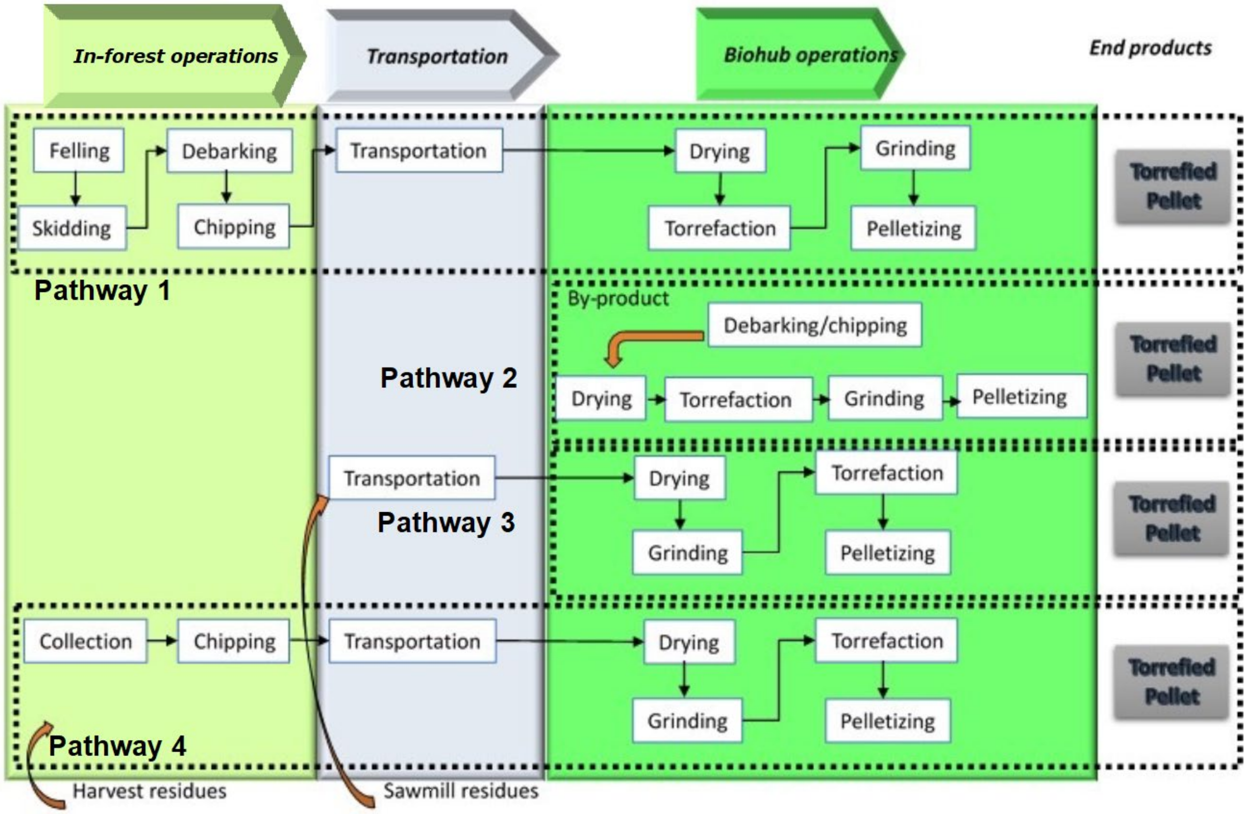


Figure 3-5: Torrefied pellet production pathways

1. In Pathway 1, the whole tree felled, skidded, debarked, and chipped in the forest. The wood chips are transported to the bio-hub to be dried, ground, torrefied, and then pelletized to produce the end product, torrefied pellets.
2. In Pathway 2, the by-products of debarking and chipping produced during various operations in the bio-hub are, as in pathway 1, dried, ground, torrefied, and pelletized to produce torrefied pellets.
3. In Pathway 3, sawmill residues are transported to the bio-hub where they undergo similar operations as the by-products in Pathways 1 and 2.
4. In Pathway 4, harvesting residues, the by-products of logging operations in the forest, are collected, chipped, and then transported to a bio-hub to produce wood chips (as in the other pathways). Logs are transported to sawmills or other facilities for further treatment.

The feedstock for the 2nd, 3rd, and 4th pathways is the wood residues from the debarking/chipping operations, the lumber industry, and tree harvesting, respectively.

3.6 Biochar

Torrefaction is a thermochemical process with a lower heating rate and temperature than pyrolysis that converts raw biomass to biochar, a coal-like material. Torrefaction, therefore, is sometimes referred to as mild pyrolysis, slow pyrolysis, or dry carbonization and occurs in an inert medium at 250-350°C with heating rates lower than 50 °C/min and residence times of 30 min to several hours [71-75]. The torrefaction products are solids and volatiles. Acetic acid and water are condensed at lower temperatures. The process conditions, primarily temperature, affect the percentage and properties of torrefaction products [73].

Torrefaction can improve raw biomass properties, thereby eliminating the challenges associated with its use. Torrefaction has received extensive interest recently because of the special characteristics of torrefied biomass and because it enhances commercial viability [72]. Torrefied biomass has better compatibility that raw biomass with pelletization, in which heterogeneous bulky feedstock is converted to a homogenous powder [72, 76-79]. Torrefaction increases carbon content and decreases oxygen content, thereby increasing the feedstock's heating value and energy density [70, 71, 78-83]. During torrefaction,bulk mass densitydecreases (due to volatile release and hence mass loss); however, energy density increases,which lowers transportation costs per unit energy content [70, 79]. Because ofdifferences in raw biomass feedstock, climate conditions, and seasonal supply,pelletization feedstock quality may vary significantly [70]. Because feedstockshave different qualities, pelletization is challenging. Moreover, having a continuous supply of large quantities of the same biomass is challenging, but it can be resolved using torrefaction prior to pelletization [70, 84].

Unlike raw biomass, torrefied biomass can be stored outside for long periods [85], eliminating the costs of a storage facility. Torrefaction makes biomass more hydrophobic [86]. During the combustion and gasification of torrefied biomass, less water vapor and smoke form(because it has lower H/C and O/C than raw biomass), thereby reducing energy loss during these processes [87].Torrefaction also reduces the energy consumption of biomass grinding by 70%-90% due to the release of the volatile components, which happens after the hemicellulose breaks down and cellulose and lignin partially decompose [70]. Torrefied biomass has a wide range of applications in various sectors including in cement kilns, power plants, the steel and coke industry, etc. [72].

Torrefied biomass or biochar is a good coal replacement because of its high quality and similar characteristics to coal (i.e., energy density). Torrefied biomass has a high consistency, unlike biomass and like coal, and so it has a similar milling requirement to coal [88]. The O/C decrease during torrefaction lowers the risk of self-ignition during grinding [89]. Torrefied biomass does not have the handling and transportation challenges of raw biomass because its heating value, density, and thus transportation costs are similar to coal's [88]. Torrefied biomass offers a stable amount of energy, unlike biomass and like coal [86]. There is no need for any infrastructural modifications in coal power plants because of the coal-compatible characteristics of torrefied biomass [72]. The looming closure of coal power plants and the replacement of coal with clean, renewable competitive fuels are the major reasons for the increased demand for torrefied biomass as fuel. There are advantages to using torrefied biomass in operational power plants because of its superior characteristics over raw biomass [72].

Biochar production pathways

The scenarios to produce biochar (torrefied biomass) are shown in Figure 3-6.

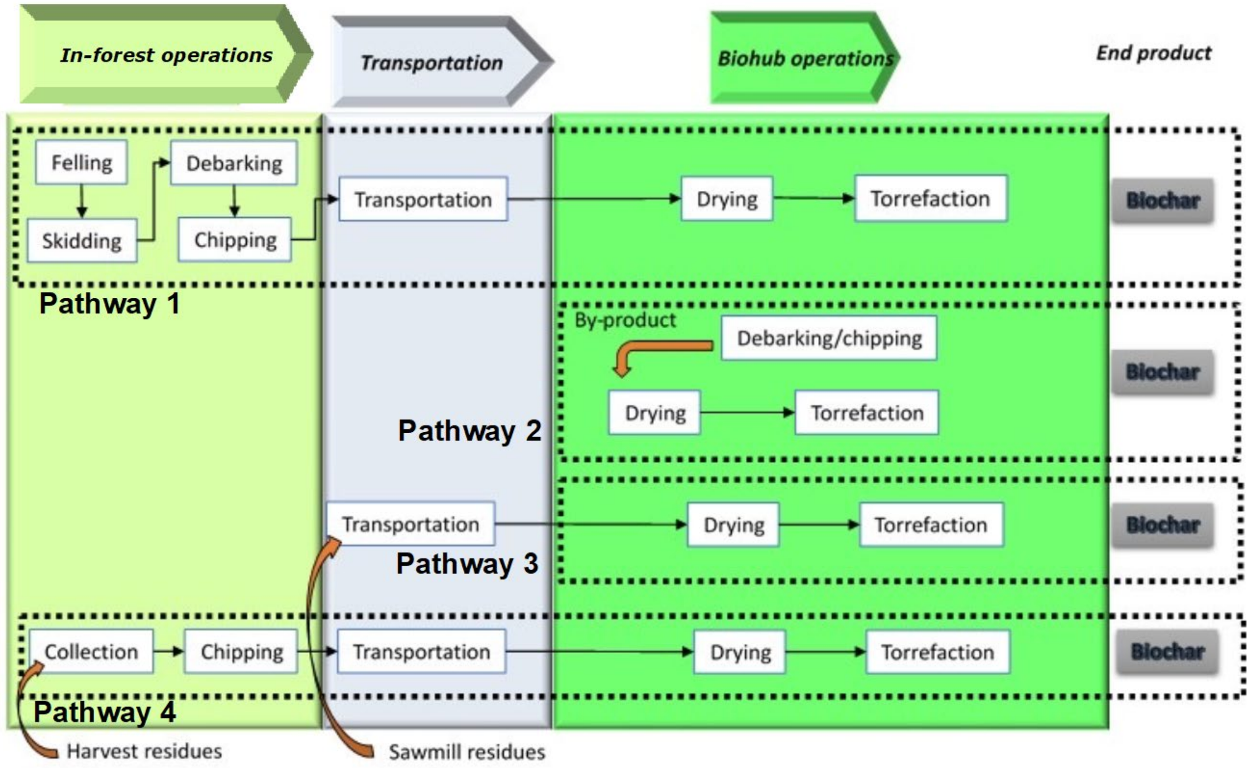


Figure 3-6: Biochar production pathways

1. In Pathway 1, whole trees are felled, skidded, debarked, and chipped in the forest. The wood chips are then transported to the bio-hub where they are dried and then undergo torrefaction, which produces the end product, torrefied biomass or biochar.
2. In Pathway 2, the by-products of debarking and chipping produced during various operations in the bio-hub are, as in Pathway 1, dried and torrefied to produce biochar.
3. In Pathway 3, sawmill residues are transported to the bio-hub where they are treated as the wood chips are in Pathways 1 and 2.

4. In Pathway 4, the residues from logging and other operations left in the forest are collected, chipped, and then transported to the bio-hub to produce biochar (as in the other pathways).

The feedstock for the 2nd, 3rd, and 4th pathways is the wood residues from the debarking/chipping operations, the lumber industry, or the harvesting of trees, respectively.

3.7 Bio-oil

Interest in biofuel as a replacement for conventional transportation fuel in North America is growing [90]. Globally, governments are supporting the use of biomass for biofuels and chemicals production [91-93]. Fast pyrolysis is a well-established technology for converting of biomass into liquid fuels. Fast pyrolysis is done in a fixed bed or fluidized bed reactor in the absence of oxygen at 400-600 °C and atmospheric pressure for a residence time of less than 2s [94-98]. The outputs of this process are bio-oil, gas, and biochar. Generally, the bio-oil yields are from 50-75 wt% depending on the feedstock and process parameters [99, 100]. Bio-oil is considered an intermediate that can be further upgraded through hydro-processing technology to produce a petro-fuel equivalent transportation fuel [101, 102].

There are various types of pyrolysis reactors, such as fixed bed, bubbling bed, fluidized bed, cyclone bed and vacuum reactor [96, 110]. Among these, the fluidized bed reactor gives the highest bio-oil yield because of proper contact between the biomass and the fluidizing medium [111]. Fluidized bed reactors are preferred over fixed bed reactors because of their better temperature distribution, lower capital investment and maintenance costs per unit output, good gas-solid contact, short residence times, and high heating rates, and their capability of handling feedstock with wide range of particle sizes [96, 97, 103]. Bio-oil produced from this process is highly viscous, acidic, and contains many oxygenated compounds, making it unsuitable for use as a transportation fuel or for blending with crude oil directly [104]. The produced bio-oil can further be treated to produce renewable diesel through chemical process like catalytic hydro-processing [105].

Many studies have been conducted on the conversion of biomass to bio-oil through fast pyrolysis [96, 106-110]. It is reported that bio-oil quality and quantity are a function of feedstock type, pyrolysis reactor, heating rate, and feed particle size distribution. The bio-oil yield differs based on the chemical and elemental composition of biomass. In this study, forest-based biomass feedstock was considered, and bio-oil production in a fluidized bed reactor through fast pyrolysis process was analyzed.

Bio-oil production pathways

The production pathways to produce bio-oil are shown in Figure 3-7.

1. In Pathway 1, the whole tree is felled, skidded, debarked, and chipped in the forest. The wood chips are then transported to the bio-hub where they are dried, ground, and screened and then pyrolyzed to produce bio-oil. Biochar is also produced during pyrolysis as a by-product.
2. In Pathway 2, the by-products of debarking and chipping produced during in the bio-hub are, as in Pathway 1, dried, ground, screened and pyrolyzed to produce bio-oil and biochar (pyrolysis by-product).

3. In Pathway 3, sawmill residues are transported to the bio-hub where they undergo similar operations as the by-products in Pathways 1 and 2.
4. In Pathway 4, the residues from logging and other operations left in the forest are collected, chipped, and then transported to the bio-hub to produce bio-oil (as in the other pathways).

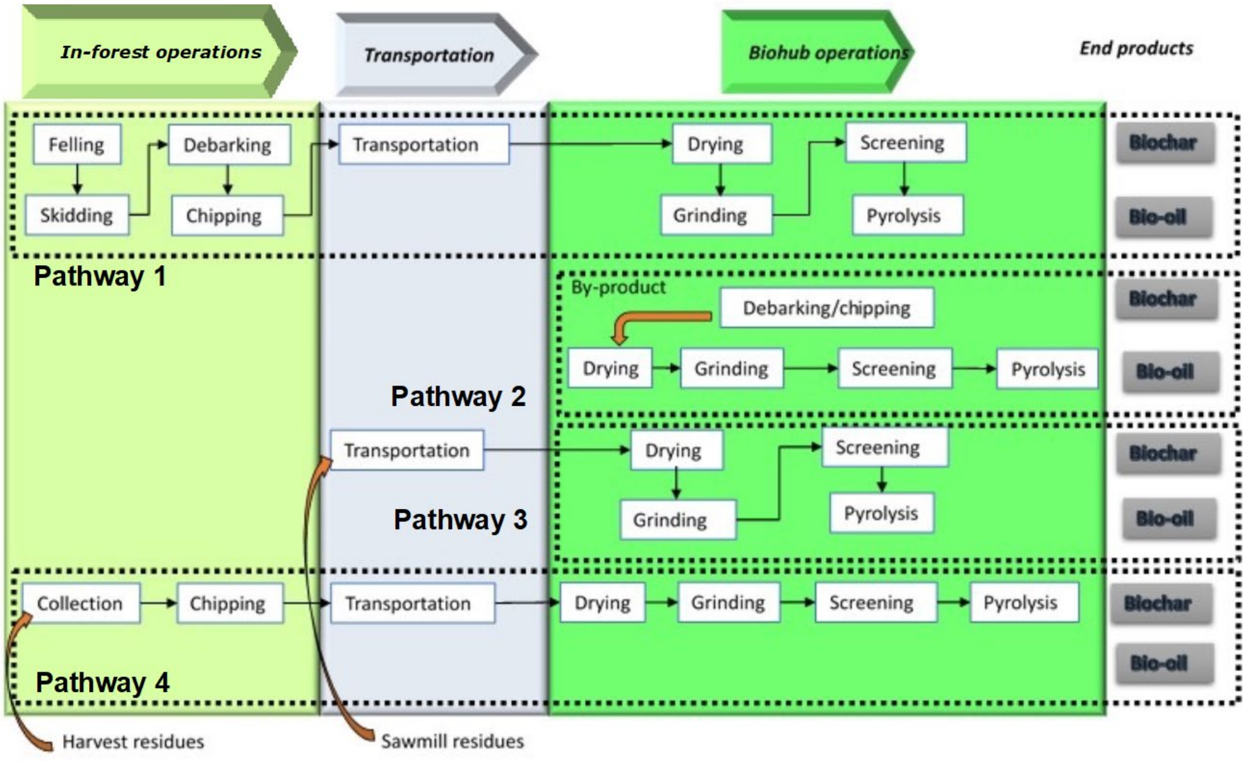


Figure 3-7: Bio-oil (and biochar as the co-product) production pathways

The collected biomass is processed in a grinder to reduce particle size. The as-received biomass has particle sizes ranging from 6 to 10 mm, which is larger than the maximum allowable size for a fluidized bed reactor. The wood chips are ground to the particle size requirements of the pyrolyzer. A lower particle size yields more bio-oil and also increases contact between sand and biomass. A gyratory crusher (grinder) is used to grind the feedstock to a suitable size for the pyrolyzer (less than 2 mm). A rectangular screen is used to separate any oversized biomass for further grinding. The as-delivered moisture content of biomass is 50% and needs to be lowered to around 8-10% by weight. Biomass is dried in a conventional dryer to reach the desired final water content. In this study, it was assumed that there are no losses of extractives or volatiles during drying and that the only exhaust from the system is moisture [50].

In fast pyrolysis, solid feedstock is converted to a liquid product (bio-oil) and by-products of gas and solid (biochar) [101, 110]. The process takes place in a sand fluidized bed reactor at atmospheric pressure and 480 °C at short residence times. The outlet gaseous stream of the reactor is passed through a cyclone separator because it contains micro-sized char particles and sand that can pollute the bio-oil. After this, the vapor enters several condensers to condense the bio-oil and the vapor temperature decreases to 40 °C from 480 °C. Then a flash column is used to separate the liquid phase (bio-oil) from the non-condensable gases. The bio-oil, non-condensable gases and biochar yields are 63%, 19% and 18% (wt%), respectively [101]. The bio-oil obtained from fast pyrolysis needs upgrading as it contains various oxygen-containing organic compounds such as ketones, acid, phenols, phenol derived, aldehydes, guaiacol, etc. The feedstock for the 2nd, 3rd, and 4th pathways is the wood residues from the debarking/chipping operations, lumber industry, and tree harvesting, respectively.

3.8 Summary

In this section, we discussed several bioproducts, namely, firewood, bark, wood chips, regular pellets, torrefied pellets, biochar, and bio-oil. The pathways for the production of these bioproducts was also discussed. Figure 3-8 shows bioproduct production pathways in bio-hubs. Firewood is mostly used for space heating in Canada and is anticipated to be a key component in the future bioenergy industry. There are two pathways to produce firewood following chipping whole trees in forests or in bio-hubs. Low-grade fuel can be produced from bark. As for firewood, debarking can be done in forests or in bio-hubs. Wood chips, a co-product from sawmill operations, is valuable for the pulp and lumber industry. Wood chips can be produced by chipping whole trees or from sawmill residues. Regular wood pellets can be used in small stoves and large-scale co-firing plants. Torrefied pellets have a better heating value and energy density than regular pellets. Both regular and torrefied pellets can be produced from whole tree and forest residues. Biochar is a clean, renewable alternative fuel to replace coal in operational power plants. Bio-oil is an intermediate for liquid fuel that can be further upgraded to a transportation fuel. Biochar and bio-oil can both be produced from whole trees and wood residues from debarking/chipping operations, the lumber industry, and the harvesting of trees.

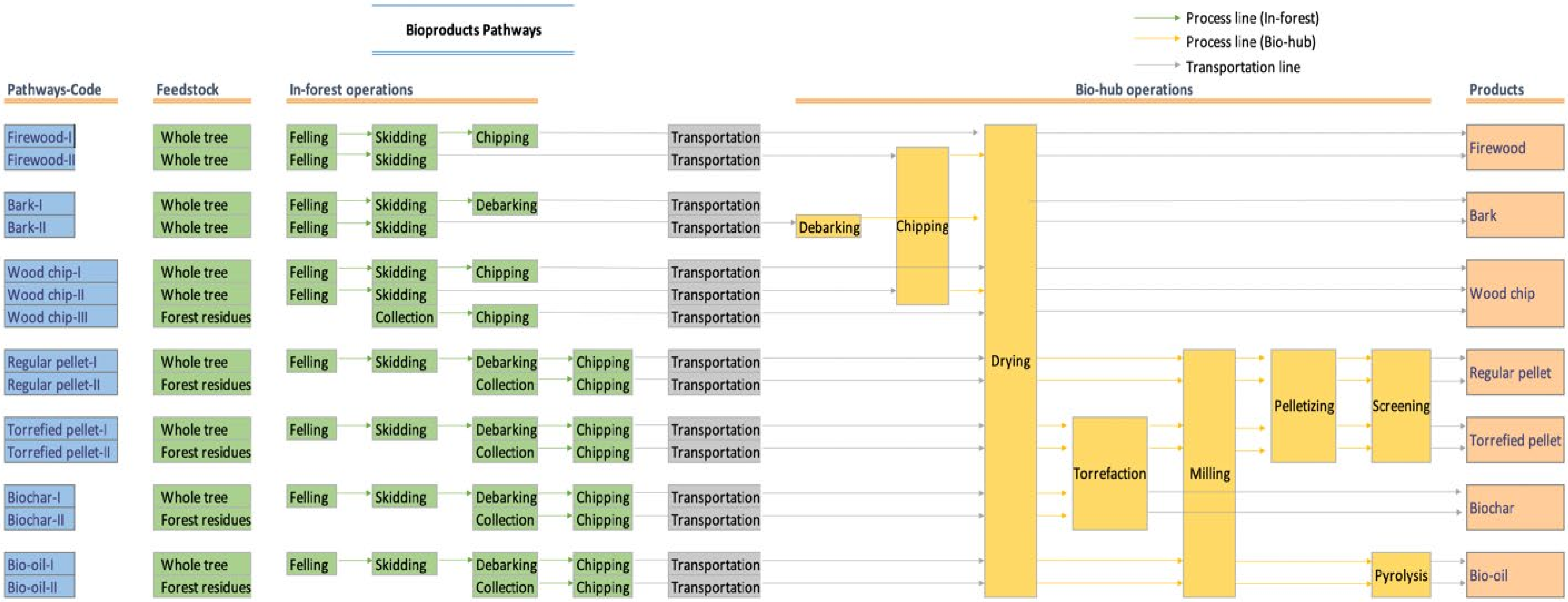


Figure 3-8: A schematic of bioproduct production pathways in a bio-hub

Section 4. Techno-economic assessment of a bio-hub

4.1 General assumptions

We identified three categories of bioproduct cost estimates: (1) in-forest operation, (2) transportation, and (3) bio-hub operation.

We developed models to estimate the costs of forest operations (i.e., felling, skidding, debarking, and chipping of the whole tree biomass) [35, 36]. We did not include road construction cost as the transportation of biomass for bio-hub will use the existing roads. Nutrient replacement cost is considered as a majority of the forest in Canada is first-generation forest and nutrient application is not a common practice. Cost components included in this study are listed in Table 4-1.

Biomass cost can differ from one producer to another and from one plant to other [112, 113]. Forest costs consist of harvesting, collection, chipping, and nutrient replacement and can include storage cost. Since no capital cost is reported for a storage facility, we assumed that the biomass is stored without the requirement of any fixed structure, and so storage cost is negligible [113]. Nutrient replacement is not considered for forest biomass. Forest residues are usually burned to prevent forest fires [114].

Table 4-1: Parameters for the calculation of biomass in-forest operations costs [46, 115]

Biomass harvesting cost	**Value (adjusted to the year 2022)($/dt)**
Felling	5.57
Skidding	4.62
Debarking	13.37
Chipping	3.57
Residue collection and chipping	14.00
Total cost	**41.13**

Transportation cost is the sum of fixed component and variable component costs. The fixed component includes the loading and unloading cost, which is estimated as $2.783/gt, based on a previously developed model [35, 36]. The variable is estimated as $0.0305/gt/km, which is a function of biomass collection radius. Furthermore, the biomass collection radius is related to biomass yield data (Table 4-2). More details on forest biomass resource yield are provided in Section 2.3. The tortuosity factor adjusts the straight-line transportation distance and is estimated to be 1.27 [127]. This factor is calculated based on geographical conditions such as swamps, hills, and lakes at the biomass site.

It is assumed that the roads built for the pulp and lumber industry are used to transport forest biomass [46]. As mentioned above, biomass transportation costs differ with the plant capacity as the area from which biomass is drawn is a function of plant capacity, and the haul distance is a function of the square root of area [46, 153]. Therefore, the economics of pellet production are sensitive to biomass yield, and higher yields per unit area decrease the area required to sustain a required capacity.

Table 4-2: Biomass yield data for whole tree biomass and forest residues for different regions in Canada

Regions	Whole tree biomass yield (dt/ha)	Forest residue yield (dt/ha)
Western Canada	83.8	23.6
Central Canada	32.8	11.6
Eastern Canada	31.0	10.5

The estimated transportation cost is usually above 5 $/dt for short hauls (1-2 km) and about 10 $/dt for a few kilometers [37]. As transportation distance decreases, costs decrease.

The total processing cost in a bio-hub was estimated based on unit operations involved for bioproduct production. The unit operations in a bio-hub are drying, torrefaction, milling, screening and pyrolysis. Debarking and chipping in a bio-hub are included in selected pathways. Table 4-3 lists the key assumptions we used to develop the techno-economic model for a bio-hub.

We developed a simulation model for the drying process to calculate mass and energy balance, which were used in the techno-economic assessment. The results of the simulation model were used to map the process equipment, and their associated sizes were calculated. The equipment cost of each unit operation was evaluated. The results of this step were used to develop the techno-economic model. The total purchased equipment cost (TPEC), utility consumption, and the number of required supervisors and operating labourers were the output of the simulation model. We calculated the total capital cost from the TPEC using the installation factors defined in the literature [116]. The total capital cost includes the costs of equipment purchase, transportation of equipment to the plant and installation as well as the associated expenses, along with the costs of land. The capital cost was assumed to be spent in a year. Although Canada has cold winters, it benefits from a well-trained workforce and construction industry that work efficiently in cold weather. Therefore, no capital cost penalty is considered here for climactic conditions.

The maintenance costs are assumed to be 3% of the initial plant capital cost [46]. Actual maintenance costs in large-scale biomass facilities significantly influence the economics of biomass plants. The operating cost and its components, i.e., plant overhead costs, operating charges, and general and administrative costs, were developed in this study. Current market prices in Canada were used to calculate different cost components including utility and labour wage unit costs.

Biomass facilities have operating outages usually a result of challenges of solids handling. To account for this, a plant capacity factor of 0.8 is assumed for plant operation [46, 152].

Table 4-3: Method and key assumptions in the development of the techno-economic model

Parameter	Value	Sources/Remarks
Method for the estimation of plant capital cost		
Total purchase equipment cost (TPEC)	100% TPEC	[152]
Total installed cost (TIC)	302% TPEC	[152]
Indirect cost (IC)	89% TPEC	[152]
Total direct and indirect cost (TDIC)	TIC + IC	[152]
Contingency	20% TDIC	[152]
Fixed capital investment (FCI)	TDIC + contingency	[152]
Location factor (LF)	10% FCI	[152]
Total project investment (TPI)	FCI + LF	[152]
Capital recovery factor (CRF)	f (plant life, interest rate)	
Annual total project investment (ATPI)	TPI × CRF	
Key assumptions for techno-economic model development		
Plant lifetime	30 years	[46]
Currency	USD	
Operating hour	8000 h/y	Assumed
IRR	10%	Assumed
Escalation rate (inflation factor)	2%	
Maintenance cost	3% of ATPI	[46]
Operating charges	25% of the operating labor cost	[46]
Plant overhead	50% of total operating labor and maintenance costs	[152]
Subtotal operating cost	Sum of operating labor, utility, maintenance, and raw material costs	[152]
General & administrative cost (G&A)	8% of subtotal operating cost	[152]
Plant capacity factor	0.8	[46,152]

4.2 Firewood

In this study, the cost of firewood is estimated to be \$46/dt for western Canada and \$48/dt for central and eastern Canada. More details on the cost breakdown can be seen in Table 4-4. Firewood price is a function of several factors including wood energy content, location, dryness, and piece size [33]. As mentioned above, hardwoods (i.e., white oak and iron wood) have higher heating value compared to softwoods (i.e., poplar and spruce) [33]. Accordingly, hardwood should be priced more as much as softwood. However, regardless of tree type, associated costs such as processing in the forest, transportation, and storage are similar [33]. Depending on the location, firewood sold in rural areas usually costs less than the firewood in urban areas [33]. Short pieces of firewood usually cost more because of the additional labour and handling requirements [33].

Table 4-4: Firewood cost breakdown for a bio-hub capacity 1500 dt/d

Parameters	Western Canada	Central Canada	Eastern Canada
Total in-forest operations cost ($/y)	$5,503,949	$5,503,949	$5,503,949
Total transportation cost ($/y)	$3,213,833	$3,804,020	$3,850,057
Total bio-hub processing cost ($/y)	$8,923,405	$8,923,405	$8,923,405
Total production cost ($/y)	$17,641,188	$18,231,374	$18,277,411
Firewood yield (dt/y)	380,000	380,000	380,000
Firewood production cost ($/dt)	$46.42	$47.98	$48.10

4.3 Bark

Bark is normally a co-product in sawmill operations. Most in-forest operations and transportation costs are accounted for in the firewood or other bioproduct production calculations, so only debarking is considered here. The cost of bark is estimated to be $13/dt. The cost value is calculated as the ratio of the annual debarking cost ($5,349,411/y) to bark yield per year (400,000 dt/y). Debarking depends on technical process configurations. Long bark lengths increase chipper efficiency. Volumetric loading is typically between 25 and 35% and drum speed is 4-7 rpm [117].

In western Canada, the transportation of residues such as bark for electricity generation is economical when the transportation distance is below 200 km [37]. However, it should be noted that the economical distance is affected considerably by the market value of the residue. When the value of the end product justifies a higher transportation cost (as is the case for sawdust), the economical distance can increase further [37].

4.4 Wood chips

In this study, a model developed by Kumar et al. for estimating chipping and transportation costs was used [46]. We assumed that whole trees are cut in the forest and skidded to a chipper (a 50/48 Morbark). The chipper is fed by a dedicated grapple. Produced chips are then loaded into a van. We assumed the chipping cost of whole trees to be $3.57/dt. The relatively lower cost compared to that from other available chippers in the study by Kumar et al. is because of the chipper's large scale (100 gt/h) and the high annual operating hours [46]. Based on their moisture content, the bulk density of wet wood chips is between 300 and 400 kg/m^3; thus, shipping by truck is not limited by volume but rather weight, given the wood chips' high moisture content [38].

The wood chip cost is estimated to be $42/dt, $38/dt, and $30/dt for pathways Wood chip-I, II, and III, respectively, for western Canada at a bio-hub capacity of 1500 dt/d (Figure 3-8). The cost breakdown for wood chip production is shown in Table 4-5. The whole tree production cost is calculated assuming harvesting and chipping costs are recovered [46].

Table 4-5: Wood chips cost breakdown for western Canada at bio-hub capacity 1500 dt/d.

Parameters	Wood chip I	Wood chip-II	Wood chip-III
Total in-forest operations cost ($/y)	$5,503,949	$4,077,440	$5,599,050
Total transportation cost ($/y)	$3,213,833	$3,213,833	$3,213,833
Total bio-hub processing cost ($/y)	$8,923,405	$10,349,915	$4,623,344
Total production cost ($/y)	$15,228,632	$13,802,123	$11,023,672
Firewood yield (dt/y)	360,000	360,000	360,000
Firewood production cost ($/dt)	$42.30	$38.34	$30.62

Residues are consolidated into piles at the roadside, chipped, and transported to the bio-hub by truck [46]. Chipping branches and tops needs different equipment than whole trees and is also less efficient. The cost of chipping is from forwarding and piling [62, 118, 119]. A specific case using forwarders, loaders, and high capacity Nicholson WFP3A chippers (48 gt/h capacity and annual operating hours of 5000 h) showed a total cost of \$14/dt to recover roadside logging residues [46]. It should be noted that the maximum chipper throughput for forest residues depends on the amount of material that can be fed into the chipper and therefore a smaller capacity chipper is used here for whole trees [46].Logging road construction and silviculture costs are not considered in the cost of harvest residues since the construction of roads and silviculture are required anyway for the forestry activities.

In most current forestry practices, as in Alberta for example, nutrients are not replaced, and the nutrients released from harvest residues are concentrated only at their collection point (the roadside) or released into the atmosphere and therefore are not available for tree regrowth [46]. Hence, the cost for nutrient replacement is not included in the harvest residues pathway, and the forest harvest residue cost here is based on the full recovery of all costs related to harvesting and chipping but without nutrient replacement [46]. A market premium of \$4/dt on the biomass results in a gain by the company that holds the cutting rights of timber. If the government requires long-term forest residue rights (and does not charge a premium for granting cutting rights), then forest residue costs will be reduced and long-term supply security will be guaranteed [46].

4.5 Regular pellets

We developed a techno-economic model to assess the cost of pellet production. The economic parameters are Canada-specific and were developed following a detailed literature review, in consultation with experts, and through process modeling. Generally, these costs include feedstock harvesting, collection, transportation, and pellet production. Capital, employee, energy, and consumables costs are the processing costs included here. Feedstock transportation cost is affected by feedstock yield. The resources considered here are found in Canada, where sufficiently large quantities of biomass can be produced to support biofuel production.

It is assumed that the pellet plant operates at 6 dt/h with a production capacity of 44,000 dt/y. Pelletization mass yield is taken as 90%, based on experiments [154]. This unit size was selected based on an earlier study's considerations on pellet plants and related barriers in having a larger size [113]. The cost parameters considered for the model development are provided in Tables 4-3 to 4-5.

Capital cost includes the costs to purchase and install process equipment for pellet production. The pellet plant capital costs are from the study by Sultana et al. [113]. The scale factor used here, from the same study, is less than 1 [113]. This implies that the capital cost per unit output decreases with the increase in the plant production capacity. Bio-fuel facilities can significantly benefit from economies of scale resulting from increased production capacity.

The optimum plant size (i.e., the size at which the cost of production is lowest). The highest manufactured unit of a pellet plant is 50,000 dt/y [113]. As expected, based on economies of scale, as the plant capacity increases up to a 50,000 dt/y, the capital cost per unit production decreases. Beyond this capacity, the capital cost per unit production increases with the capacity increase as two smaller unit size plants are built (e.g., at 60,000 dt/y, two units of 30,000 dt/y are built; this has a higher capital cost per unit production compared to a plant of capacity 50,000 dt/y). This affects the optimum size of the pellet plant.

Table 4-6: Pellet production plant costs

Plant equipment	Scale factor	Capital cost ($)	Maximum size of equipment (dt/y)	Source
Dryer	0.6	430,000	100,000	[113]
Hammer mill	0.6	150,000	108,000	[113]
Pellet mill (with conditioner)	0.85	350,000	50,000	[113]
Pellet cooler	0.58	170,000	216,000	[113]
Screener/shaker	0.6	18,300	108,000	[113]
Bagging system	0.63	450,000	108,000	[113]

Table 4-7: General assumptions

Equipment power used for energy	Value (kW)	Source
Primary grinder	112	[113, 118]
Dryer	120	[113, 118]
Hammermill	75	[113, 118]
Pellet mill	300	[113, 118]
Cooling	5	[113, 118]
Bagging	40	[113, 118]
Light and heat	112	[113, 118]

Biomass facilities have operating outages that are usually due to challenges of solids handling [46]. To account for this, an operating factor of 0.8 is assumed for plant operation. The operating cost includes the costs of energy, labour, and consumables. The energy cost includes the costs of natural gas and electricity. The electricity cost is calculated using wattage information from each piece of equipment [121]. Feedstock drying requires natural gas. The natural gas cost is calculated according to the energy requirement of each piece of equipment from the process model, details of which are from an earlier study [50]. Labour cost is the main cost in pellet production. Two types of laborers were considered here, permanent, and hourly. Four permanent and 7 hourly laborers are required for pellet production at a production rate of 44,000 dt/y [113].

In this study, the production cost of regular pellets was calculated to be $118/dt and $85/dt for whole tree and forest residue biomass, respectively, for western Canada at a capacity of 500,000 dt/y (Table 4-8). Other regions have slightly higher pellet production costs. Other studies have assessed the economics of biomass facilities for energy production through generic models [113, 114, 118, 122-124]. Mani et al. reported sawdust pellet production cost to be $51/dt at a capacity of 45,000 t [125]. Thek and Obernberger predicted the production costs of sawdust-based pellets in a European jurisdiction [126]. Urbanowski estimated the capital cost of a pellet plant [127]. The production cost of pellets in Europe and other locations has been studied by other researchers [121, 128-130]. Region-specific data is available for the delivered cost of different feedstocks in Canada.

4.6 Torrefied pellets

The transportation cost of torrefied pellets depends on volume and is a function of the density of the product. The techno-economic assessment includes capital and operating cost estimates for both the torrefaction and the pelletization units. Since torrefied pellets have a higher bulk density than regular pellets, their transportation cost is lower than regular pellets'. This amount, however, cannot be exactly defined as it depends on the effectiveness of the pelletization of the torrefied feedstock [79]. The ratio of the torrefied pellet volume to the conventional pellet volume is used to estimate the transportation cost of torrefied pellets [71]. The handling and transportation costs of torrefied pellets can be calculated based on the associated costs for conventional pellets [79]. This ratio indicates how much energy fuel with a specific volume contains [79]. The market value of pellets produced depends on their fuel properties [79].

The method used to assess the production costs of torrefied pellets in abio-hub is similar to that used to assess the production costs of torrefied biomass and pellets. Torrefied pellet production costs include wages for laborers and personnel, utilities costs, raw material costs, and delivered feedstock costs, which include both feedstock and feedstock transportation cost.

The production cost of torrefied pellets was calculated to be $157/dt and $120/dt for whole tree and forest residue biomass, respectively, in western Canada in a bio-hub at a capacity of 500,000 dt/y. Details on cost breakdown for are given in Table 4-8.

Table 4-8: Pellets cost breakdown for western Canada for a bio-hub capacity 1500 dt/d

	Regular pellets		**Torrefied pellets**	
Parameters	**Whole tree**	**Forest residues**	**Whole tree**	**Forest residues**
Total in-forest operations cost ($/y)	$13,566,700	$6,998,812	$13,566,700	$6,998,812
Total transportation cost ($/y)	$3,213,833	$3,144,016	$3,213,833	$3,144,016
Total production cost ($/y)	$41,281,582	$29,812,800	$48,757,805	$37,289,022
Pellets yield (dt/y)	349,200	349,200	311,137	311,137
Pellets production cost ($/dt)	$118.2	$85.4	$156.7	$119.8

4.7 Biochar

Techno-economic models were developed through economic assessments and process modeling to assess the economic viability of a plant. Mass and energy balances were calculated in the process model. The total purchased equipment cost (TPEC), utility consumption, and number of laborers were estimated using the process model. The capital cost includes the location factor and contingencies. Current market rates in Canada were used for electricity and labor cost estimates. The production costs of biochar were then estimated through the developed techno-economic model. The technical and economic parameters considered in this section, from earlier studies [29, 113, 132-139], are shown in Table 4-3.

Table 4-6 shows the elemental analysis of wood chips (pine chips were considered here) studied. The plant input feedstock capacity is assumed to be 264 dt/d (11,000 dry kg/h). According to Akbari et al. and Svanberg et al., economies of scale are achieved at this capacity [141, 142].

Table 4-9: Feedstock and torrefaction process characteristics studied [140]

Feedstock	Moisture content (%)	Elemental analysis				Torrefaction process conditions
		C	H	N	O	T (°C), t (min)
Wood chips	45	49.82	6.61	0.04	43.29	297, 30

We adapted the plant configuration for the process from Bergman et al. [83]. This configuration uses the thermal energy of hot flue gas leaving the combust or to dry the feedstock prior to the torrefaction reactor [83]. The torrefaction reactor requires the feedstock's moisture content to be 10 wt% (wet basis) [143, 144]. Depending on the feedstock moisture content, the flue gas energy may be enough for both biomass drying and torrefaction [72], or it may cover some part of the dryer's energy requirements. The degree of torrefaction defines how much energy the flue gas can provide and determines mass loss and combustible volatiles amounts [72]. Drying prior to torrefaction is crucial because higher moisture in the reactor leads to higher torrefaction gas moisture, thereby lowering the adiabatic flame temperature. A negative consequence of a wet torrefaction gas is incomplete combustion, as there is not enough energy in the torrefaction gas to reach the minimum temperature of 900 °C, where complete combustion occurs [72]. Therefore, the biomass moisture content in the reactor is considered to be 10%.

The unit operations were simulated (Figure 4-1). Torrefaction happens at around atmospheric pressure [83], hence the reactor pressure was considered 1 atm in the simulation. The biochar produced is cooled immediately to lower the risk of autoignition [74]. Consequently, the solid product enters the heat exchanger, and the gaseous part is directed to the combustor. Even though the moisture content of input biomass to the reactor is only 10 wt% (wet basis), water vapor makes up the highest portion of torrefaction gas, followed by CO_2, neither of which is combustible. The moisture content of a biochar product was assumed to be 1.05 wt% (wet basis) in the simulations [143].

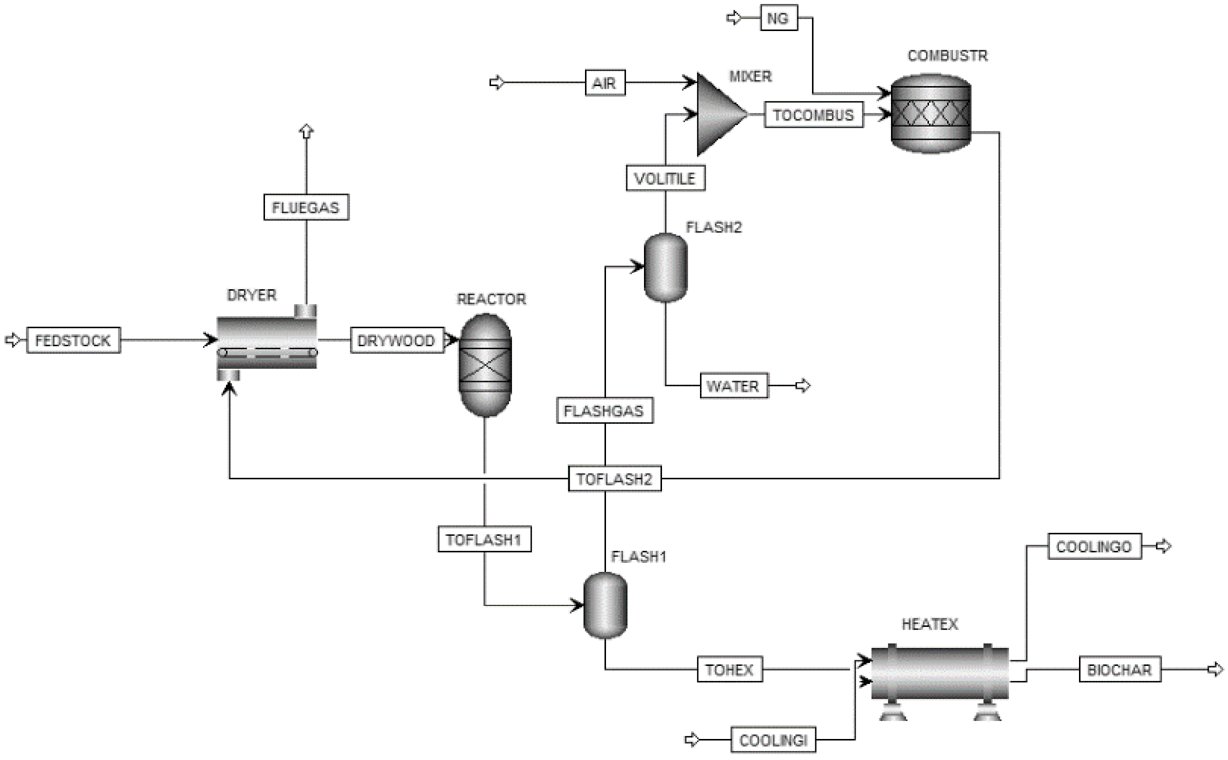


Figure 4-1: Process flow simulation diagram for biochar production

The production cost of biochar is estimated to be \$87/dt and \$65/dt for whole tree and forest residue biomass, respectively, in western Canada at a bio-hub capacity of 500,000 dt/y (Table 4-10).

Table 4-10: Biochar cost breakdown for western Canada for a bio-hub capacity 1500 dt/d

	Biochar	
Parameters	**Whole tree**	**Forest residues**
Total in-forest operations cost (\$/y)	\$13,566,700	\$6,998,812
Total transportation cost (\$/y)	\$3,213,833	\$3,144,016
Total production cost (\$/y)	\$27,849,183	\$20,680,462
Pellets yield (dt/y)	320,000	320,000
Pellets production cost (\$/dt)	\$87.03	\$64.63

4.8 Bio oil

The process model for fast pyrolysis and upgrading technology was developed using both experimental and other published data (Figure 4-2). Aspen wood chips (*Populus tremuloides*) were chosen as the feedstock for modeling. The feedstock properties are given in Table 3-2.Theprocess model was used to evaluate the equipment costs. In the process model, each piece of equipment was mapped and sized to the design parameter (obtained from published sources and vendor data). The techno-economic model development method (summarized in Table 4-3) was used to assess the total plant cost. Installation costs include equipment, piping, electrical, installation and building yard improvement [116]. The indirect cost includes legal expenses, contractor's fee, construction expenses, and engineering and supervision costs. The direct costs include regional laborers and utility rates.

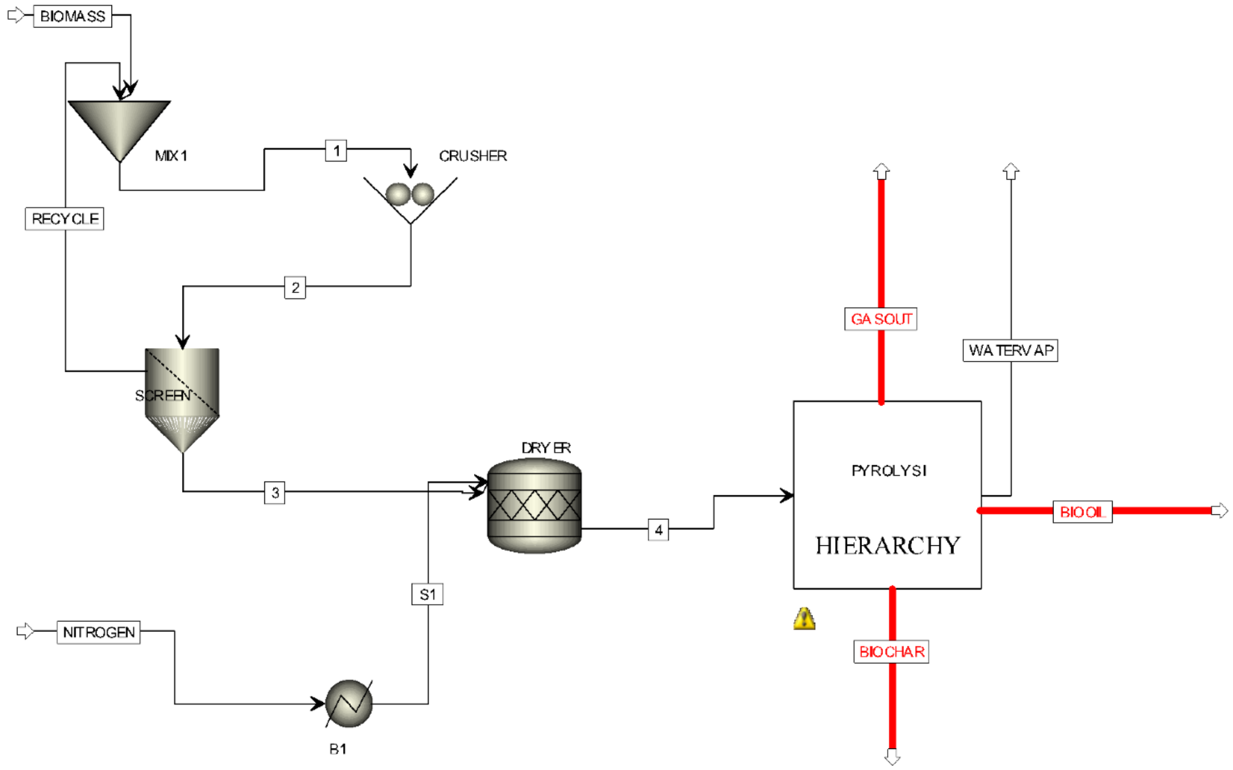
Table 4-3 shows the key characteristics of the plant assumed here; these characteristics were used in an earlier study to calculate the costs [145]. Using the developed techno-economic model, we estimated the bio-oil production cost. Variable operating costs include operating labor, raw material, plant overhead, maintenance, operating charges, general and administrative, utilities costs, and waste disposal. The delivered biomass cost has two components: biomass production cost and biomass transportation cost [46, 145].

Fast pyrolysis is a relatively well understood and has been demonstrated at large scale, and there are many TEA studies on bio-oil production from biomass. The production cost of bio-oil has been estimated to be between \$0.13/L and \$0.65/L [103, 118, 147, 148]. In this study, the production cost of bio-oil was calculated to be \$0.49/L and \$0.46/L for whole tree and forest residues, respectively, at a bio-hub capacity of 500,000 dt/y. It is reported that the total capital cost of a 1000 dt/d pyrolysis plant is between \$40 M and \$150 M [149, 150]. In this study, the total investment is estimated to be \$139 M for a 1000 dt/d pyrolysis plant. There are differences in bio-oil production costs due to feedstock type, biomass cost (harvesting and transportation), bio-oil yield, and capital cost for pyrolysis facilities. Biomass cost depends on location, yield, cultivation method, and transport.

Table 4-11: Proximate and ultimate analyses of aspen wood chips

Parameter	Value	Parameter	Value
Proximate analysis, mass fraction (%)[a]		**Ultimate analysis, mass fraction (%)[a]**	
Ash	0.66	Nitrogen	0.12
Volatile	82.97	Carbon	46.97
Fixed carbon	15.96	Hydrogen	5.98
		Sulfur	0
		Oxygen	43.9

[a] All calculations are on a dry weight basis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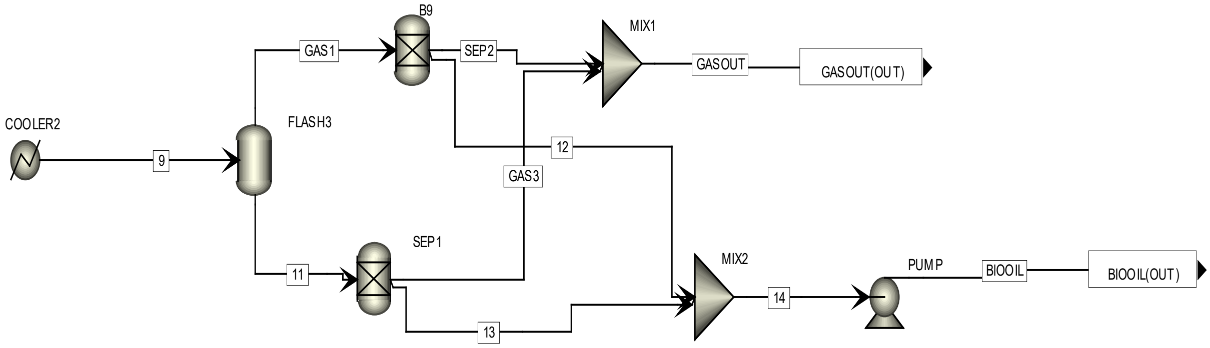
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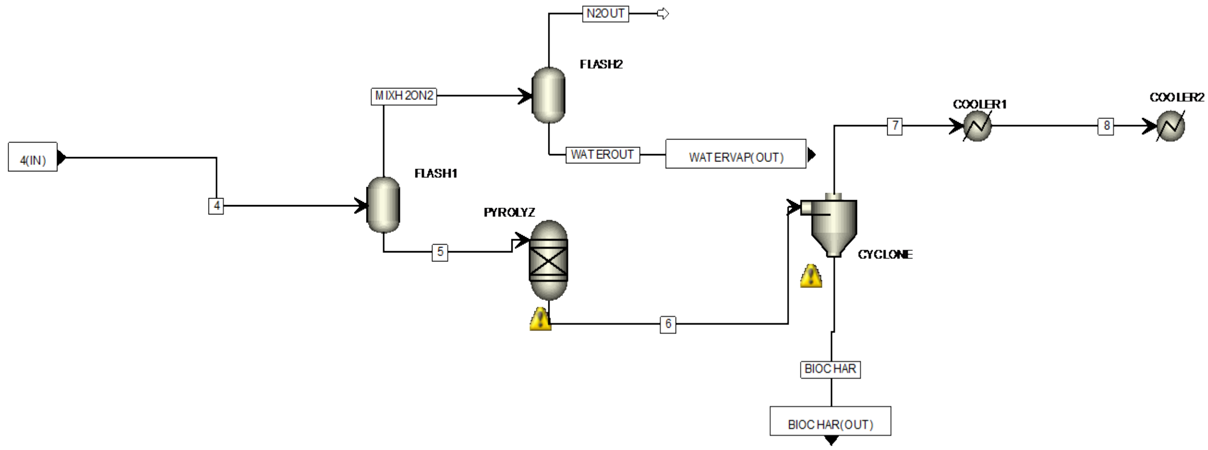


Figure 4-2: Process flow simulation diagram for bio-oil production

4.9 Summary

We developed techno-economic models for several bioproducts produced in a bio-hub at various process configurations in western, central, and eastern Canada. Under specific conditions (location: western Canada; feedstock: whole tree; capacity: 500,000 dt/y), the production costs of firewood, bark, wood chip, regular pellet, torrefied pellet, biochar, and bio-oil were estimated to be $46/dt, $13/dt, $38/dt, $118/dt, $157/dt, $87/dt, and $0.49/L, respectively.

Section 5. Development of the techno-economic assessment tool – CANBIO-HUB (Version 1)

5.1 The TEA tool: CANBIO-HUB

In this section, we describe the spreadsheet-based techno-economic analysis (TEA) tool (CANBIO-HUB) we developed to estimate the costs of various bioproducts at the bio-hub. The tool has a user-friendly interface and provides cost values of bioproducts under different input conditions. The section also describes various features and techno-economic parameters for users to select bioproducts considering cost and location. This modeling tool is intended to assist in economic decision-making in the context of a bio-hub in Canada.

5.2 Method

The cost estimation TEA tool, CANBIO-HUB, was developed through a Visual Basic package (Microsoft Visual Basic for Applications 7.1). This tool is dedicated to cost estimations for a bio-hub in Canada, as described in earlier sections.

In Visual Basic, Canada is divided into three regions, western, central, and eastern. Biomass resource information for each region is stored in a datasheet. Biomass resource potential is estimated in terms of biomass yield (whole tree and forest residues), as discussed in Section 2. There is no need for the user to enter the biomass data; the user needs only to select the region of interest. As described earlier, CANBIO-HUB has three parts – in-forest operating cost estimation, transportation cost estimation, and bio-hub cost estimation. The in-forest cost for whole trees is the sum of all costs related to felling, skidding, debarking, and chipping. The in-forest cost for forest residues is the residue collection and chipping costs. In the feedstock section of CANBIO-HUB, the user selects either “Whole tree” or “Forest residues.” The bio-hub capacity is then modeled and used to estimate bioproduct costs based on user-defined targets of a bio-hub capacity. An overview of the CANBIO-HUB is shown in Figure 5-1.

CANBIO-HUB is a software package that takes 3 main types of user input:

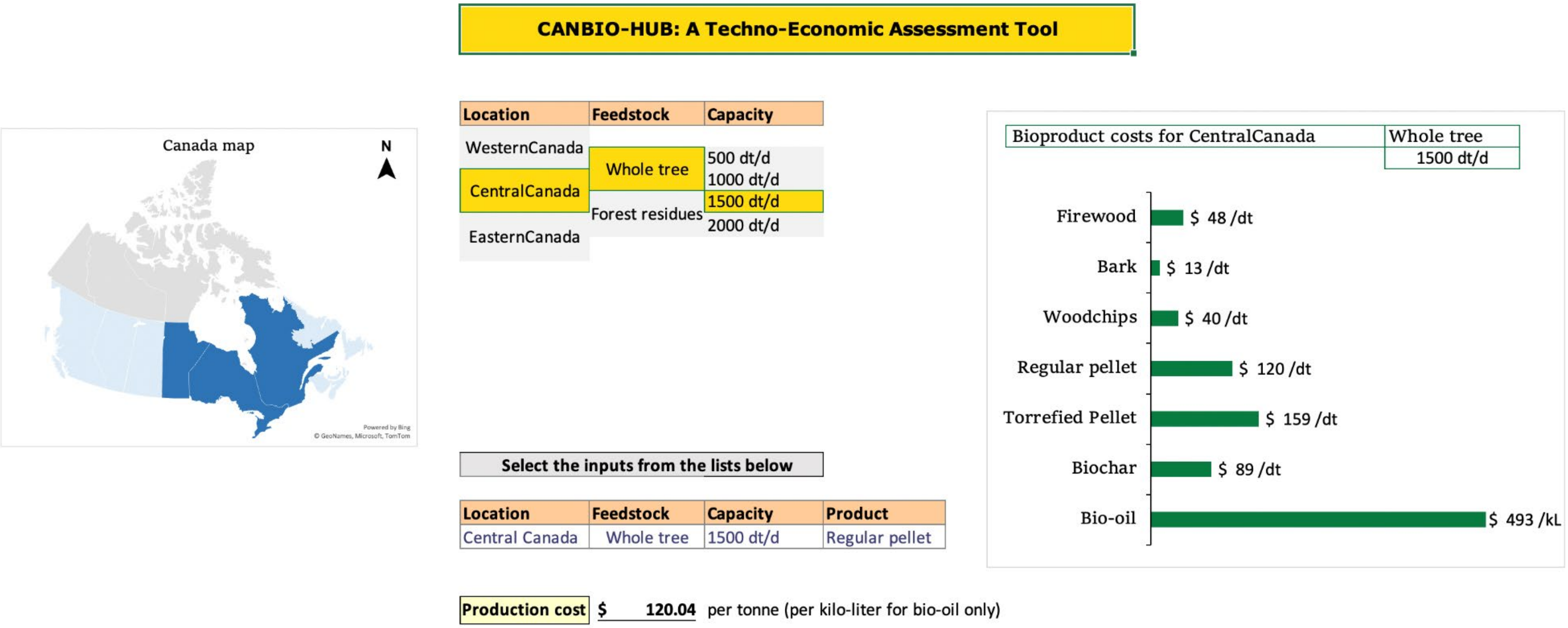
1) Location or region (the choices are western Canada, central Canada, and eastern Canada),

2) Feedstock (the choices are whole tree and forest residues), and

3) Capacity of bioproduct production (the choices are 500 dt/d, 1000 dt/d, 1500 dt/d, and 2000 dt/d).

CANBBIO-HUB provides bioproduct costs for a selected set of inputs as outputs. The output bioproduct costs are 1) firewood, 2) bark, 3) woodchip, 4) regular pellet, 5) torrefied pellet, 6) biochar, and 7) bio-oil costs.

The user can change key financial inputs like plant capacity factor, discount rate, interest rate, annual operating hours and others, outside the dashboard (i.e., the bio-hub product cost estimation tool). An overview of the dashboard is shown in Figure 5-1.



CANBIO-HUB: A Techno-Economic Assessment Tool

Location	Feedstock	Capacity
WesternCanada	Whole tree	500 dt/d
CentralCanada	Forest residues	1000 dt/d
EasternCanada		1500 dt/d
		2000 dt/d

Select the inputs from the lists below

Location	Feedstock	Capacity	Product
Central Canada	Whole tree	1500 dt/d	Regular pellet

Production cost $ **120.04** per tonne (per kilo-liter for bio-oil only)

Bioproduct costs for CentralCanada	Whole tree
	1500 dt/d

Figure 5-1: An overview of CANBIO-HUB (Version 1)

5.3 How to use CANBIO-HUB

There are two ways to determine bioproduct costs:

1) Use the interactive dashboard (preferable)
2) Use the drop-down menu to select inputs

<u>For Option 1</u>

Example: To determine the cost of bioproducts from whole tree biomass produced in a 1500 dt/d capacity bio-hub located in central Canada, the user should

- Select “Central Canada”
- Select “Whole tree”
- Select “1500 dt/d”

The costs will appear in the dashboard (as shown in Figure 5-2).

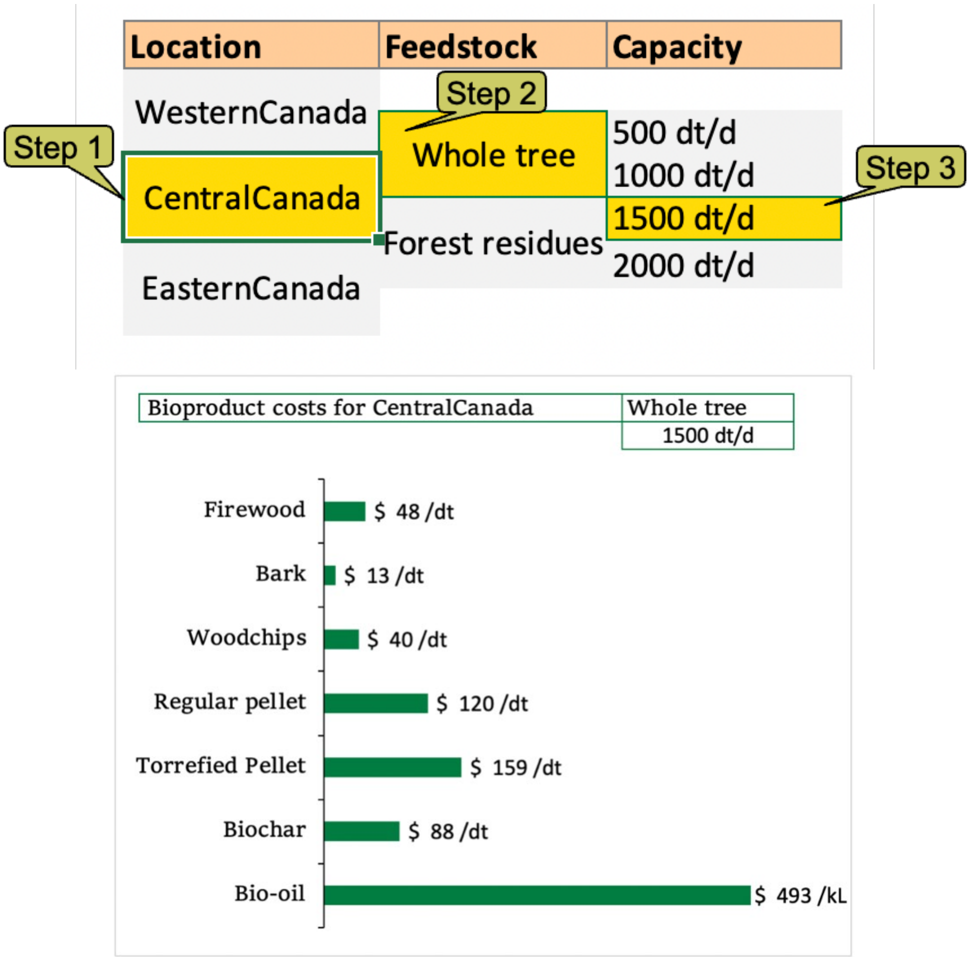


Figure 5-2: CANBIO-HUB’s interactive dashboard (Option 1)

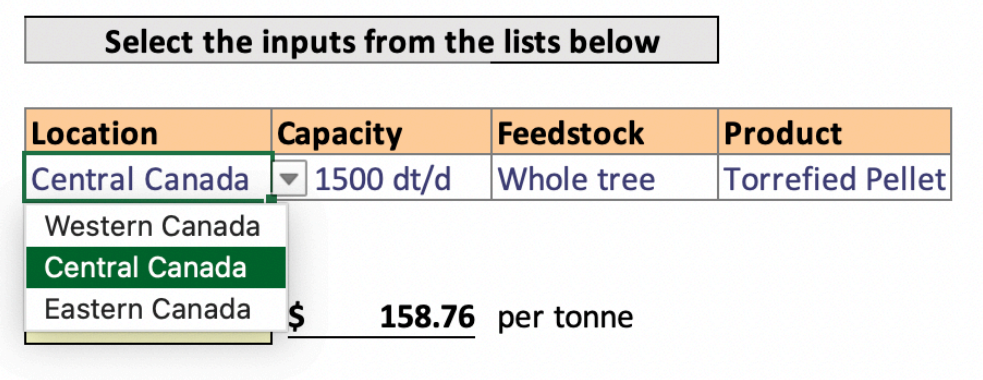
For Option 2

Example: To determine the cost of torrefied pellets from whole tree biomass produced in a 1500 dt/d capacity bio-hub located in central Canada,

- Select “Central Canada” from the “Location” drop-down menu
- Select “1500 dt/d” from the “Capacity” drop-down menu
- Select “Whole tree” from the “Feedstock” drop-down menu
- Select “torrefied pellet” from the “Product” drop-down menu

The production cost will appear, as shown in Figure 5-3.

Step1

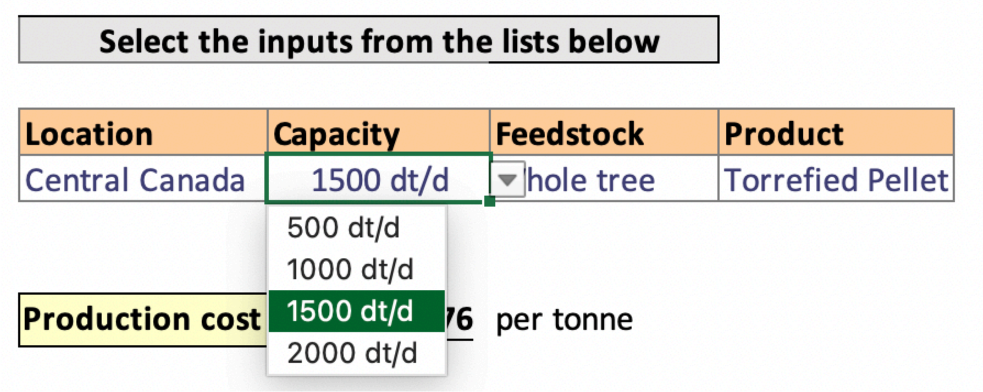


Select the inputs from the lists below

Location	Capacity	Feedstock	Product
Central Canada	1500 dt/d	Whole tree	Torrefied Pellet

$ 158.76 per tonne

Step2

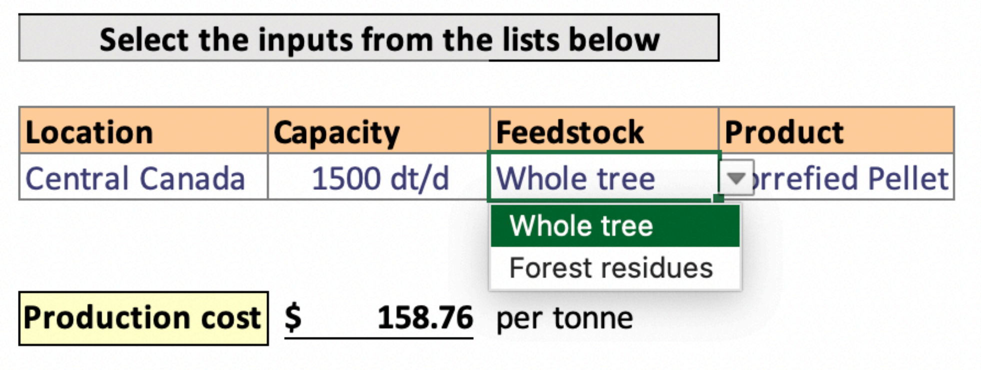


Select the inputs from the lists below

Location	Capacity	Feedstock	Product
Central Canada	1500 dt/d	hole tree	Torrefied Pellet

Production cost 76 per tonne

Step3

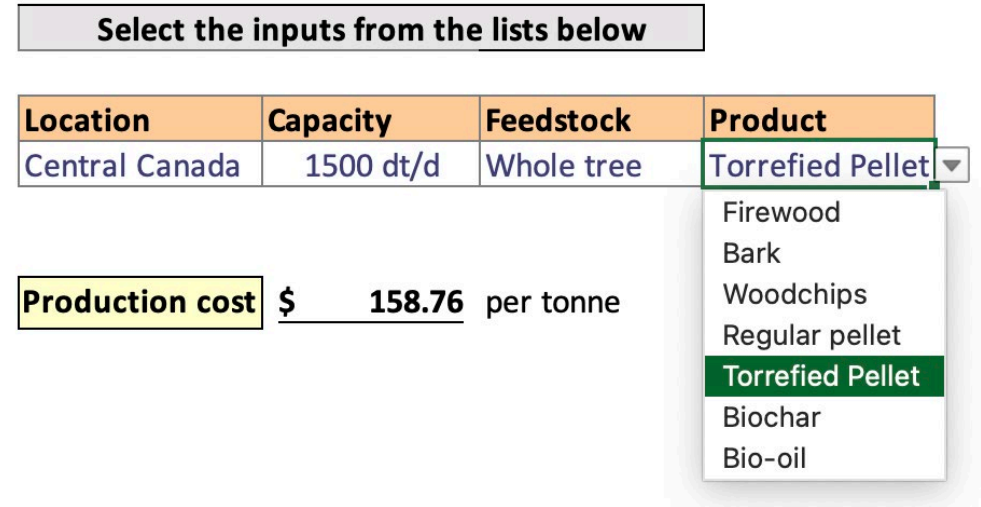


Select the inputs from the lists below

Location	Capacity	Feedstock	Product
Central Canada	1500 dt/d	Whole tree	rrefied Pellet

Production cost $ **158.76** per tonne

Step4



Select the inputs from the lists below

Location	Capacity	Feedstock	Product
Central Canada	1500 dt/d	Whole tree	Torrefied Pellet

Production cost $ **158.76** per tonne

Figure 5-3: Using the CANBIO-HUB's drop-down menus (Option 2)

5.4 Limitations

CANBIO-HUB has the following limitations:

- The tool does not allow one to choose multiple feedstocks for utilization simultaneously;
- The dashboard could be designed with more economic parameters;
- The current version's calculator does not account for varying operating costs, such as utilities and labor costs, at different regions; and
- The tool could be more robust with further detailed engineering inputs.
- The tool is specific to Canadian forestry biomass but the input data can be adjusted for estimation of bioproduct costs in other jurisdictions outside Canada.

Section 6. BIOSALIX: A case study analysis

6.1 Background

The BIOSALIX project has its genesis as an innovative solution at the nexus of the key challenges of large scale mine reclamation, biosolids management, climate change mitigation, and energy transition. These challenges were addressed via the establishment of a short-rotation coppice willow plantation. SYLVIS Environmental Services formed a collaborative group including EPCOR Water Services, Westmoreland Mining, Natural Resources Canada – Canadian Forest Service, and Bionera Resources Inc. to implement the project vision. The project received funding from the Natural Resources Canada Clean Growth Program and the Emissions Reductions Alberta Partnership Intake Program and Alberta Innovates granting agencies.

BIOSALIX is anchored in the beneficial use of biosolids to improve willow establishment by amending marginally productive soils characteristic of reclaimed mines and to augment existing soil resources. To achieve this goal, approximately 12,000 dry tonnes of biosolids were transported from EPCOR's Gold Bar Wastewater Treatment Plant to Westmoreland's Paintearth Mine near Forestburg, Alberta. Biosolids were applied to a spectrum of reclamation areas to facilitate growth of willows and rectify reclamation trajectories via amendment addition to improve soils tilth, fertility, and organic matter status. Willows were planted into biosolids amended soils at rates up to 20,000 stems per hectare using specialized planting equipment in combination with conventional agricultural practices. This crop may be considered a renewable resource obtained from a biomass plantation cultivated on reclaimed land and should be integrated with end uses affiliated with appropriate biomass conversion technologies. The project relied on contributions of trained mine operators and local planting crews, providing diversified training and economic development opportunities within the regional labour force.

At this time, the case studies are conducted with the goal of developing techno-economic models and a tool for use by industry, government, and other stakeholders to understand the cost of various products from bio-hubs. This is a desktop exercise that requires data input from the participants on the projects being included. The BIOSALIX project has been selected for inclusion based on its status as an example for the broader concept of a regional bio-hub where multiple partners are involved. There is additional value to the project in that it develops fast-growing crops and addresses municipal biosolids residuals. The actual data from BIOSALIX was used to validate the results of CANBIO-HUB.

6.2 Willow plantation establishment

The process flow diagram for a willow biomass plantation establishment, fertilized with biosolids, for the purpose of mine reclamation is shown in Figure 6-1.

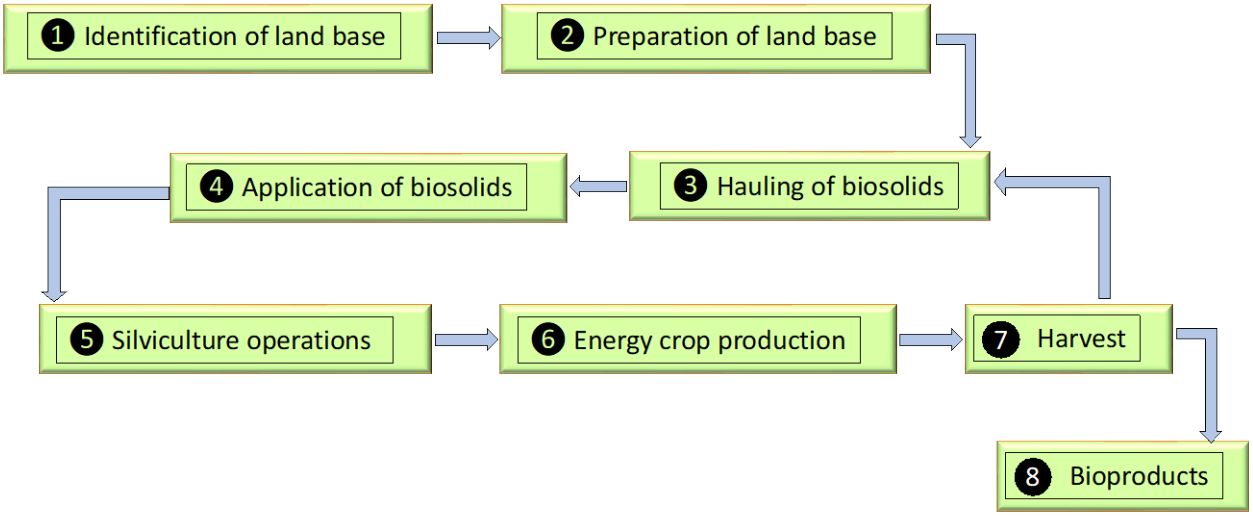


Figure 6-1: Process-flow diagram for a willow plantation establishment

The following basic steps are generally followed:

1) Identification of land base
    a) Land likely to benefit from reclamation and available for inclusion in the project is identified.
    b) Soil is sampled to determine its eligibility for the application of biosolids and suitability to support willow establishment and growth.
    c) A regulatory submission seeking authorization to apply biosolids within or outside of the *Guidelines for Application of Municipal Wastewater Sludges to Agricultural Lands* (Government of Alberta, 2001) is developed.
2) Preparation of land base for receiving biosolids (rock removal is required to reduce potential damage to planting equipment)
    a) A rock rake or ripper pulled by a tractor is used to bring rocks to the surface. Smaller rocks are rolled into rows for pickup by a rock picker and boulders are removed by an excavator or backhoe.
    b) A rock picker pulled by a tractor removes rocks from fields. This may be done two or more times if a field is rocky.
3) Hauling of biosolids
    a) Material is hauled from the Edmonton Waste Management Centre to Paintearth Mine using tandem-quad haul trucks that carry approximately 37 bulk tonnes of biosolids per load. This is approximately 190 km with a one-way run time of just over two hours.
    b) The material is delivered to designated temporary stockpiles on site where it remains until applied to the land. There are temporary stockpiles affiliated with particular fields where biosolids are applied and an all-weather stockpile in a central location where biosolids are delivered when conditions are not suitable at the temporary stockpiles.
4) Application of biosolids
    a) Biosolids are applied using manure spreaders pulled by tractors with a loader operating at the stockpile to load the spreaders.
    b) Pre-planting takes place and may be redone in conjunction with the three-year harvesting cycle.

5) Planting of willows
    a) A chemical herbicide is applied to the field to assist with weed control before planting.
    b) The land is cultivated to prepare the soil for planting.
    c) A planter pulled by a tractor plants the willows. The project uses Egedal and bulk-billet planter types.
    d) After planting, a pre-emergent herbicide is applied before the willows reach the bud-break stage.
6) Weed control in the willow plantation
    a) Mechanical and chemical weed control methods are used as required during the first two growing seasons until canopy closure is achieved. Mechanical control includes specially adjusted rototillers for cultivating weeds in the row-to-row spacing between willow rows, and chemical control includes praying herbicide over the field.
7) Harvesting of willows
    a) This occurs every three years when the willows are dormant, typically during the winter months. A harvester goes down the rows of willows and puts the harvested material on a receiving wagon being pulled by a tractor adjacent to the harvester.
8) Allocation of biomass to economic or growth uses
    a) If the material is harvested as billets with the intent to plant, it will have to be transported to a central location, stored appropriately, and cold-stored until planting to maintain viability.
    b) Overall, the biomass will be allocated to end uses based on requirements and opportunities at the time of harvest. Short-term requirements may include planting harvested billets to augment or expand willow plantation areas or chipping the material for use as a feedstock in soil fabrication. Feasible mid-term paths for directing the biomass may include biofuels/bioenergy, biomass conversion, and engineered composites. Biochemical pathways require infrastructure development in Alberta, so long-term paths may be available in the future.
9) Return to 3) Hauling of biosolids – where biosolids will fertilize the newly harvested plantation to support the next three years of growth.

6.3 Economic evaluation

For a maximum willow yield of 20 dt/ha with a harvest cycle of 3 years, the willow yield was found to be 13002 dt/y. Willow production costs were estimated to be 88.6 $/dt (or 44.3 $/gt) using the CANBIO-HUB tool.

Section 7. Whitesand: A case study analysis

7.1 Background

Bio-hubs serve as bioeconomy centres for storage, loading and processing, where the biomass may be transported to industries through different means.

A proposed bioeconomy centre project located in northern Ontario was chosen by the Ontario government as a case study to validate techno-economic models for bio-hubs.

The project proposes to use the new energy source (6.5 megawatt) to provide energy to a new wood pellet plant for local economic development through the production and export of wood pellets. This proposed facility could also serve as a bio-hub to distribute logs for hardwood plywood and softwood lumber and use woody residues, undersized trees, and underused species for fuel.

There are studies focused on the availability and costs of fibre from the forest to the biomass centre [29, 46]. A more holistic assessment of wood supply and costs to the bioeconomy centre and other regionally significant mills will help assess the initial project and the feasibility of the additional bio-hub concept. The aim of the project is to better understand the economic feasibility of establishing a bio-hub in the northern Ontario community selected for this study.

7.2 Case study

The proposed bioeconomy project is assumed to be located about 250 km from a currently receiving pulp and paper mill and sawmill. Opportunities may exist to benefit from the merchandising yard in the bioeconomy centre if the hardwood is taken to the centre and exchanged with softwood. This would help reduce hauling costs for hardwood by shortening the distance from the forest to the receiving facility (as opposed to receiving mills ~250 km away), as well as by reducing the driving time for an empty truck. In addition, the need to use hardwood from far distances will be avoided. Hardwood is sent to the bioeconomy centre at cost of \$41.88 to \$54.60/m^3.

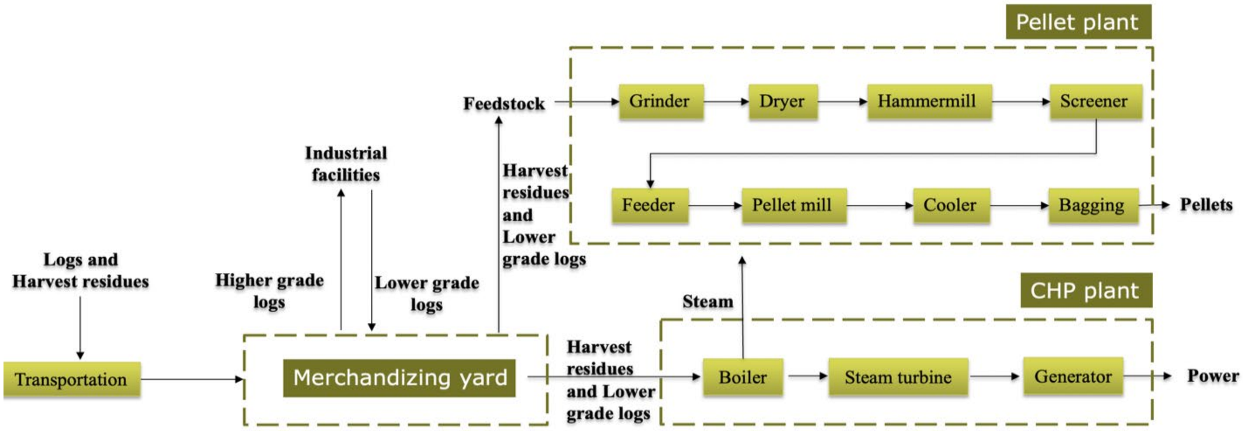


Figure 7-1: A process-flow diagram of a typical bioeconomy facility in central Canada.

There are other types of bio-hubs in mill facilities in central Canada. For example, a large facility in northern Ontario uses chips from its sawmills and in-bush chipping operations to feed the pulp mill. Sawmill planer shavings are used to fuel the boilers for the kilns. Sawdust is made into pellets for electricity generation at a power plant in the region. Roadside slash at an economical distance (less than 100 km) provides hog fuel for the steam boilers and turbines to produce 60 MW of electricity for the grid. A variety of chemicals from the pulp mill such as tall oil are sent to biorefineries. This might be called a vertically integrated bio-hub.

7.3 Summary

This case study contributes to an interest in the role of bio-hubs in the bioeconomy by the governments of Canada and Ontario. The study also strengthens the feasibility assessment of the planned bioeconomy centre by taking a holistic look at the wood movement under different wood sorting scenarios.

The merchandizing yards for the bio-hubs in Europe that merchandize and sort forest products to recover higher value and/or exploit a more efficient transportation configuration do not exist in central Canada. The main difference between these regions are the product and market diversity/density, as well as the road infrastructure, with central Canada having more commodity-based markets, sparser infrastructure, and significantly higher hauling distances. These factors seem to inhibit the cost recovery from additional wood handling in the merchandizing yards of a bio-hub.

In northern Ontario, the hardwood cost is from \$41.88 to \$54.60/m^3. For a whole tree density of 0.5 gt/m^3 at 50% moisture content, the hardwood cost is typically about \$41 to \$54/dt. In comparison, the CANBIO-HUB shows a cost of \$48/dt for firewood production in central Canada.

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Section 8. Conclusions

Around 10% of the energy consumed globally is produced from biomass resources [74, 151]. Some challenges with biomass facilities have limited their progress and use. The quality and quantity of biomass feedstock varies considerably; this makes large-scale biomass use in a biomass-based facility challenging. Generally, biomass feedstocks have low density, heating value, and yield (the quantity produced per unit area). All of these bring high biomass delivery costs, leading to high biomass conversion costs [46]. In view of the above, this report presents the techno-economic model, CANBIO-HUB, developed in this study for Canada. In summary:

1. Several forest management activities used in Canadian provinces were reviewed.
2. The method for the development of models that enable biomass quantification was discussed in detail.
3. The products considered in this study that could be produced in a bio-hub are firewood, bark, wood chips, regular pellets, torrefied pellets, biochar, and bio-oil.
4. Pathways for biomass processing and the production of bioproducts in a bio-hub were developed, and the different life cycle stages involved in the production of each product were illustrated. The processes are summarized as follows:
    a. Firewood production comprises felling and skidding trees in the forest, chipping (either in the forest or the bio-hub), transportation to the bio-hub, and drying.
    b. Bark production includes felling and skidding trees in the forest followed by debarking (either in the forest or the bio-hub). One of the pathways investigated is the transportation of bark from a sawmill to a bio-hub.
    c. Wood chip production includes felling and skidding trees in the forest, chipping (either in the forest or the bio-hub), transportation to the bio-hub, and drying. The other pathways assessed are the transportation of sawmill residues to the bio-hub and drying; using the by-products of bio-hub processes to produce wood chips; and the collection and chipping of harvest residues in the forest, transporting them to the bio-hub, and drying.
    d. Pellet production includes tree felling, skidding, debarking, and chipping in the forest; transporting chips to the bio-hub; drying, grinding, screening; and pelletizing in the bio-hub. The other pathways, also concluding with pelletizing in the bio-hub, are the transporting of sawmill residues to the bio-hub; using bio-hub residues; and the collection and chipping of harvest residues in the forest and transporting them to bio-hub.
    e. Torrefied pellet production includes felling, skidding, debarking, and chipping trees in the forest; transporting the chips to the bio-hub; drying, torrefying, grinding; and pelletizing in the bio-hub. The other pathways, with the same operations in the bio-hub, are the transporting of sawmill residues to the bio-hub; using bio-hub residues; and collecting and chipping harvest residues in the forest and transporting them to the bio-hub.
    f. Biochar production includes felling, skidding, debarking, and chipping trees in the forest and transporting the chips to the bio-hub to be dried and torrefied. The other pathways, with the same operations in the bio-hub, are the transporting of sawmill residues to the

bio-hub; using bio-hub residues; and collecting and chipping harvest residues in the forest and transporting them to the bio-hub.

g. Bio-oil production includes felling, skidding, debarking, and chipping trees in the forest, followed by transportation to the bio-hub; and drying, grinding, screening, and pyrolyzation in the bio-hub. The other pathways, with the same operations in the bio-hub, are the transporting of sawmill residues to the bio-hub; using bio-hub residues; and collecting and chipping harvest residues in the forest and transporting them to the bio-hub.

5. The models show a minor difference in production cost of various bioproducts at different bio-hub locations. For a bio-hub capacity 500,000 dt/y (1500 dt/d), the cost values of firewood production from whole trees were estimated to be $46.40/dt, $47.90/dt, $48.10/dt, for western Canada, central Canada, and eastern Canada, respectively. For the same capacity, the woodchip production cost was estimated to be $38/dt for western Canada and $40/dt for both central and western Canada. The production cost values of regular pellets and torrefied pellets were $118/dt and $157/dt, respectively, for a bio-hub capacity 1500 dt/d located in western Canada. The production cost values of pellets for central and eastern Canada were $120/dt and $158/dt for regular and torrefied pellets, respectively. Biochar production cost values were estimated to be $87/dt for western Canada and $89/dt for both central and eastern Canada at a bio-hub capacity of 1500 dt/d. The bio-oil production cost value was estimated to be around $490/kL for all three regions in Canada. All cost values for bioproducts discussed above refer to whole tree biomass feedstock.

6. Using the CANBIO-HUB tool, under a given condition (location - western Canada; feedstock - whole tree; capacity - 500,000 dt/y), the production costs of firewood, bark, wood chips, regular pellets, torrefied pellets, biochar, and bio-oil are estimated to be $46/dt, $13/dt, $38/dt, $118/dt, $157/dt, $87/dt, and $0.49/L, respectively. The method of developing CANBIO-HUB to calculate the production cost of the end product has been detailed in the report. The assumptions and technical and economical parameters involved in the calculations were summarized in tables throughout the report.

7. The developed CANBIO-HUB tool can be useful for all stakeholders. The financial outputs are based on annualized capital and operating cost estimates. The TEA tool was validated through two case studies. This tool can be used for project planning and investment decision by various stakeholders.

Future work

The following areas should be studied in future.

1. Biomass availability in terms of type and quantity for three regions in Canada (western, central, and eastern Canada) should be investigated to determine the general configuration of bio-hubs in each region.
2. Techno-economic models should be developed for several other feedstocks including agricultural residues and municipal solid waste through detailed process modelling for the different bio-hub processing pathways.
3. The overall production cost and a selection of feedstocks supplied at the bio-hubs by region should be calculated.
4. CANBIO-HUB, the techno-economic assessment tool, should be further improved to estimate the cost of bioproducts in bio-hubs under different process settings.
5. CANBIO-HUB should be validated with a case study from eastern Canada.
6. In future, a web-based dashboard should replace the current visual basic TEA tool.
7. The assessment of the environmental impacts of the production of different pathways is of interest. This will include improving the capability of CANBIO-HUB so that it can be used to estimate the life cycle greenhouse footprint of different bioproducts.

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